

AFFTC-TIM-04-08



**LIMITED EVALUATION OF THE AUTOMATIC  
FORMATION FLIGHT CONTROLLER  
(PROJECT SOLO FORM)**

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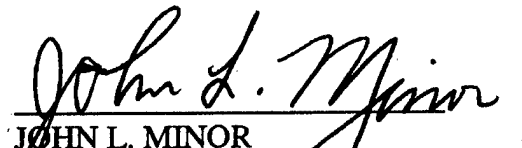
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## EXECUTIVE SUMMARY

Automatic formation flight control is the automated control of aerospace vehicles in relation to other aerospace vehicles. The computer algorithms used to generate the required aircraft flight control inputs were the subject of an Air Force Institute of Technology (AFIT), Department of Aeronautics and Astronautics (AFIT/GAE-05) student thesis work by Major Ryan Osteros. Central to the thesis was the Automatic Formation Flight Controller (AFFC), a compilation of computer control algorithms that generated aircraft commands based on inputted formation state parameters. This document presents the technical information memorandum of the USAF Test Pilot School (TPS) Class 04A test program, Project Solo Form, to provide flight test data of the AFFC.

The test program was sponsored by the USAF TPS Test Management Program Curriculum. The responsible test organization was the 412<sup>th</sup> Test Wing with test execution being performed by members of USAF TPS 04A. General Dynamics Advanced Information Systems (GD-AIS) and Bihle Applied Research provided additional test support.

The overall objective of this test was to gather flight test data in order to determine the performance of the AFFC system as applied to a two-ship formation of aircraft. Maneuvers for the simulated lead aircraft were generated by a computer aircraft simulator system for use during ground simulation and flight testing. Flight testing utilized the Variable Stability In-Flight Simulator Test Aircraft (VISTA) NF-16D, USAF S/N 86-0048. The AFFC algorithm was implemented into the VISTA Simulation System (VSS) and controlled the VISTA for the autonomous formation flight tests. The virtual lead aircraft was generated real-time in the simulator and data-linked from a modified control room at the USAF TPS to the VISTA via a Situation Awareness Data-Link (SADL). VISTA flight data and virtual lead aircraft data were recorded.

Five test sorties for a total of 8.0 flight test hours were flown from 25 to 27 October 2004. All test missions operated out of Edwards AFB, CA within the Air Force Flight Test Center's open-air range in Restricted Area R-2508. The USAF TPS performed data collection and a limited evaluation of the controller performance. All test objectives were met.

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# INTRODUCTION

## Background

Automatic formation flight control is the automated control of aerospace vehicles in relation to other aerospace vehicles. Close formations are necessary for future missions envisioned for unmanned aerial vehicles (UAVs), to include long-range tanker flight in close formation for fuel savings (Reference 1), automated aerial refueling, multi-ship target attack formations, and long-term close formation manned flight for the purposes of fuel savings or weather penetration safety. Different computer algorithms used to generate the required aircraft flight control commands were the subject of Air Force Institute of Technology (AFIT) research work, and the Automatic Formation Flight Controller (AFFC) represented the most current thesis work in this area.

Testing was requested by the Air Force Institute of Technology, AFIT/GAE-05, Wright Patterson AFB, OH by Major Ryan Osteros, TPS/EDA, AFIT/GAE-05, and Thesis Advisor Dr. David Jacques AFIT/SYE, 2950 Hobson Way, Wright Patterson AFB, OH 45433-7765. The responsible test organization was the 412<sup>th</sup> Test Wing (412 TW), Air Force Flight Test Center (AFFTC), Edwards AFB, CA. Five members of the USAF Test Pilot School (TPS) Class 04A functioned as the Solo Form test team and executed the test.

The few previous attempts at actual close formation flight control were limited by the number of axes of control or by the maneuverability of the lead aircraft. Automatic formation flight was conducted as part of a previous USAF TPS test management project SELF SERVE that included a close formation control algorithm. This algorithm maintained a final formation position after other control algorithms effected an autonomous tanker rendezvous (Reference 2).

The original AFFC system developed in conjunction with the AFIT thesis (Reference 3) was coded in a MATLAB Simulink® model that included the lead and trail aircraft dynamics as well as the aerodynamic interaction between the two aircraft. It was meant to provide long-term, stable formation flight control of the trail aircraft despite operationally-representative maneuvering of the lead aircraft. In addition to performing formation hold, the controller was capable of performing limited formation position changes. A second version of the AFFC was developed for the purposes of testing on the Variable Stability In-Flight Simulator Test Aircraft (VISTA) aircraft and was provided to General Dynamics Advanced Information Systems (GD-AIS) for aircraft integration. A single set of control gains was developed for flight. The specific gains chosen were meant to provide a stable response to all formation hold and position change maneuvers.

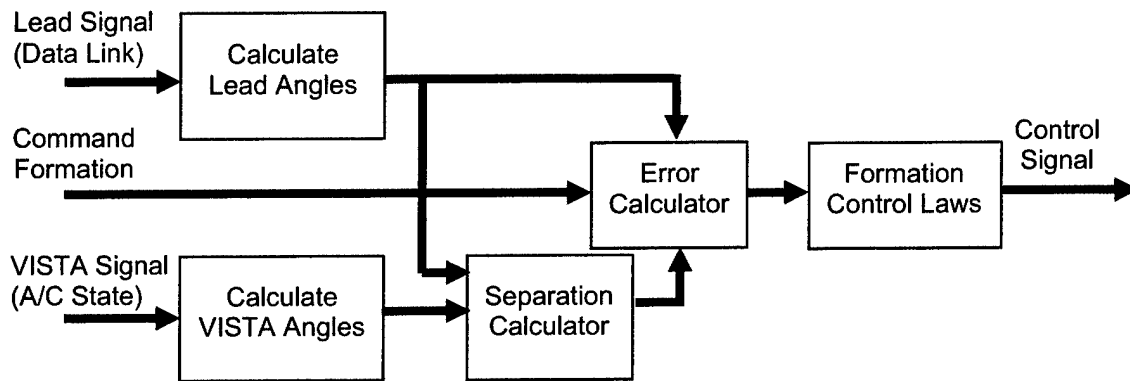
In addition to collecting data to analyze the performance of the AFFC, the test program also examined the formation-hold and formation-change maneuvering from an operational, man-in-the-formation perspective.

## Program Chronology

Five test sorties were flown from 25 to 27 October 2004 for a total of 8.0 flight test hours. All test missions operated out of Edwards AFB, CA within the Air Force Flight Test Center's open-air range in Restricted Area R-2508.

## Test Item Description

The test item was the Automatic Formation Flight Controller system previously discussed. The control system was loaded as software into the memory of the VISTA aircraft. A complete description of the controller is located in Appendix C. Figure 1 is a functional representative of the AFFC controller.



**Figure 1 – Diagram of AFFC Functions**

The same signals were received into the AFFC system for both the virtual lead and the VISTA aircraft. These signals were used to calculate flight path and course angles for both aircraft. The inertial separation vector between the two aircraft was calculated and represented in the VISTA's control axes. The commanded formation was an input to the error calculator along with the actual separation and other lead and VISTA state parameters. Six different error states were calculated next and fed into the control laws. The control laws utilized proportional and integral feedback to drive the error states to zero and resulted in a control signal to the VISTA aircraft.

The NF-16D VISTA (USAF S/N 86-0048) was a modified F-16D Block 30 Peace Marble II (Israeli version) aircraft with a Digital Flight Control System (DFLCS) using Block 40 avionics and powered by the F110-GE-100 engine. To allow the pilot in command to fly from the aft cockpit, all necessary controls were moved from the front to the aft cockpit. The aft cockpit had conventional F-16 controls except that the throttle was driven by a servo, which followed the electrical commands of the front cockpit when the VISTA Simulation System (VSS) was engaged. The primary VSS controls, displays, and system engagement were located

in the aft cockpit. The front cockpit included the VSS control panel needed to engage the variable-feel center or side stick, but the VSS could only be engaged from the aft cockpit. The front cockpit Multi-Function Displays (MFDs) reflected the aft cockpit MFDs and could be used for simulation configuration control if necessary. The Head-Up Display (HUD) symbology was fully programmable. Other modifications to the aircraft included a higher flow rate hydraulic system with increased capacity pumps and higher rate actuators as well as modifications to the electrical and avionics systems required to support VSS operations.

The VSS consisted of three flight-qualified digital computers which interfaced with the NF-16D DFLCS, associated sensors, signal conditioners, and displays. For in-flight simulation, VISTA used VSS feedback gains to model unaugmented response characteristics. The VSS computers also hosted the flight control laws, which allowed VISTA to generate closed-loop response characteristics. VISTA had the capability to change selected flight control gains during the course of a flight using either MFDs or stored programs. The VSS also included built-in test functions, Vehicle Integrity Monitor (VIM) and disengagement logic, disengagement reporting, and manual disengagement capability (Reference 4).

This test of the AFFC system used a virtual lead aircraft data-linked to VISTA. The virtual lead was a nonlinear, six-degree-of-freedom model simulated by DSix using USAF Innovative Control Effector (ICE) UAV dynamics. Virtual lead aircraft position data was sent from a computer running DSix in the USAF TPS control room to a SADL for broadcast to VISTA. The current position of the virtual lead relative to the current position of VISTA was displayed in (x, y, z) format on the VISTA HUD.

## **Overall Objective**

The overall objective of this test was to gather flight test data in order to determine the performance of the AFFC system as applied to a two-ship formation of aircraft. The two specific objectives were to (1) determine the in-flight position-keeping errors of the AFFC algorithm and (2) conduct a qualitative assessment of computer controlled aircraft maneuvers for the mission of manned automatic formation flight.

## **Limitations**

During formation maneuvers in which the virtual lead aircraft was decelerated, the ICE UAV dynamics created a deceleration rate that was too great for the VISTA to match using only throttle commands for airspeed control. The test pilots were able to activate the VISTA speedbrakes to aid its deceleration. However, the performance of the AFFC was thereby corrupted by the manual speedbrake effects. As a result, the evaluation of decelerating maneuvers was unsuccessful.

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# TEST AND EVALUATION

## Overall

The overall test objective was met. All testing was conducted at Air Force Flight Test Center (AFFTC), Edwards Air Force Base, California from 25-27 October 2004. The test team flew five NF-16D test sorties for 8.0 hours.

## Test Objectives

The first specific test objective was to determine the in-flight position-keeping errors of the Automatic Formation Flight Controller (AFFC) algorithm. Flight test positional data for the virtual lead and the Variable Stability In-Flight Simulator Test Aircraft (VISTA) were collected as a measure of performance.

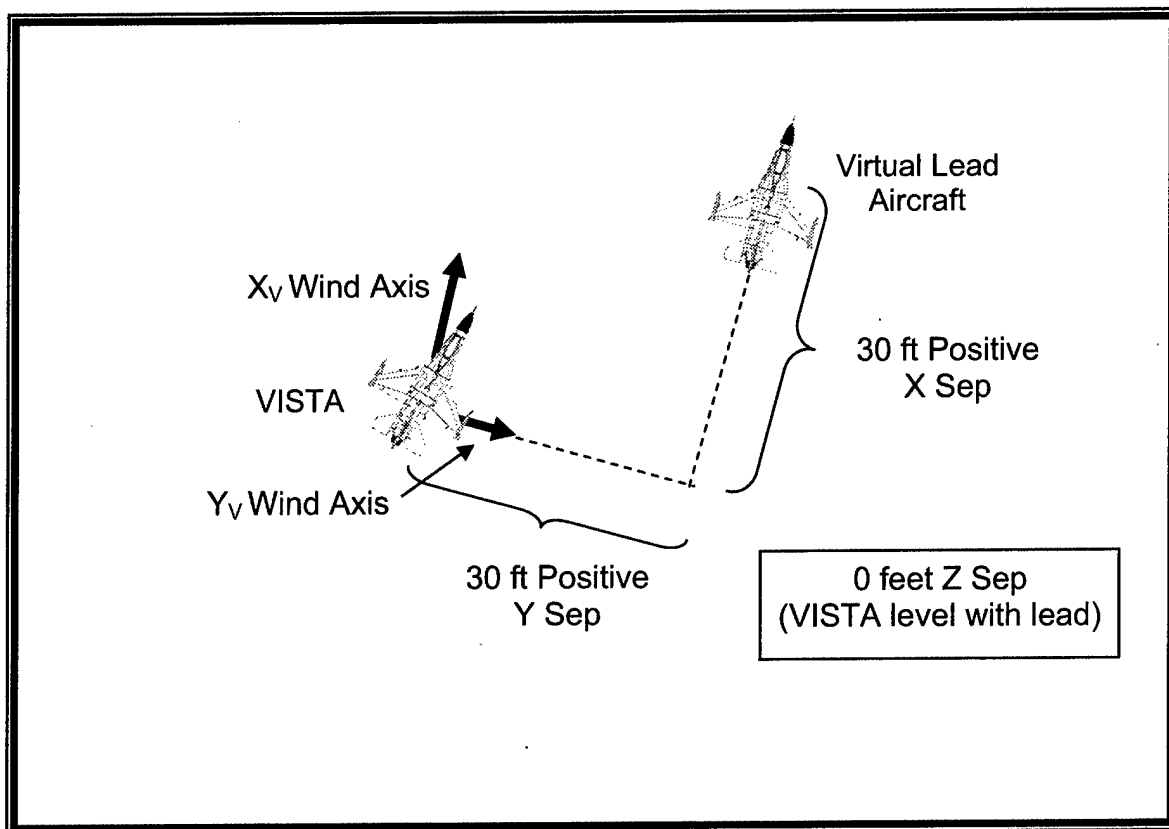
The second specific test objective was to conduct a qualitative assessment of computer controlled aircraft maneuvers for the mission of manned automatic formation flight. Pilot qualitative comments were collected as a measure of performance using the post-flight questionnaire presented in Appendix B.

## Test Procedures

The flight test was controlled from Test Pilot School (TPS) Control Room A with the VISTA flying within data link range of the control room (approximately 20 nautical miles). Prior to commencing each test point, the VISTA was stabilized in level, unaccelerated flight on a heading that minimized the headwind component of the winds aloft. The nominal flight condition was 20,000 feet pressure altitude and 667 feet/second ground speed (396 knots true airspeed in still air) in cruise configuration.

The DSix computer in the control room used VISTA position, heading, velocity, and altitude data received over the Situation Awareness Data Link (SADL) to calculate the initial conditions of the virtual lead aircraft based on the standard formation position (Figure 2). The lead aircraft position and altitude were then transmitted back to the VISTA over the SADL. After verifying a successful initialization, the aircrew released the control stick and rudder pedals and engaged the controller. The VISTA was then maneuvered as necessary with manual throttle control and automatic stick control into the standard formation position. Once in position, the aircrew fully engaged the controller, including the automatic throttle control. Depending on the specific test point, the control room then commanded a virtual lead aircraft maneuver, or the aircrew commanded the AFFC to a new formation position.

Following the termination of each test point, the procedures were repeated for the next maneuver. In cases where the VISTA was in the desired formation position following a test point, the initialization procedures were unnecessary, and the control room simply commanded the next virtual lead maneuver, or the aircrew commanded the AFFC to the next formation position. AFFC position-keeping data were recorded onboard VISTA for each test point to support the test objective. Additionally, DSix-generated virtual lead parameters and the SADL data were recorded internally on the DSix computer in the control room.



**Figure 2 – Test Standard Formation Position (30, 30, 0)**

Following each flight, the test pilot recorded qualitative impressions of AFFC performance and suitability from an operational, man-in-the-formation perspective. The results of the post-flight questionnaire are presented in Appendix B.

## RESULTS AND ANALYSES

### In-Flight Position-Keeping Errors

Results are divided into each of the maneuver types that were flown during the flight test. For clarity, each maneuver's results are explained, the appropriate performance metrics are presented, and references to the time history plots are provided for comparison. The maneuvers were divided into three major categories: lead maneuvering while VISTA held a constant position, VISTA changes position while lead held straight and level, and lead combination maneuvers while VISTA held a constant formation. Due to the previously discussed limitation with the Innovative Control Effector (ICE) dynamics, the virtual lead aircraft could not support the determination of position-keeping errors for decelerating maneuvers. **Determine position-keeping errors of the Automatic Formation Flight Controller during decelerating maneuvers with a virtual lead aircraft that decelerates at a rate slower than the controlled aircraft (R1)<sup>1</sup>.**

#### Lead Maneuvers with VISTA in Standard Position

##### Lead Acceleration (Event 4A)

Starting in straight, level flight with the VISTA in standard formation position, the lead aircraft performed a velocity change of 50 knots using an acceleration of approximately 1.5 knots/second. The standard formation position was defined as 30 feet to the left of lead, 30 feet aft of lead, and level with lead vertically. Two runs were accomplished and compared, with the results from the runs presented in Figure 14 and Figure 15. Plots a through c display, on the same graphs, the lead and wingman states to identify what maneuvers are being accomplished. Plots d through g display the x-channel, y-channel, and z-channel separations and the total separation of the aircraft. The x-channel, y-channel, and z-channel separations were defined as the distance between the VISTA and lead centers of gravity in the VISTA wind-axis reference frame along the x, y, and z axes, respectively (Figure 2). Total separation was simply the absolute distance between the centers of gravity in inertial space. The AFFC algorithm closely matched the velocity of the lead aircraft after a short hesitation of less than 1 second at the beginning the acceleration, probably due to the engine spooling up. The VISTA's change in velocity frequently resulted in a climb of up to 20 feet before the controller compensated for the change in the flight condition.

Approximately 8 seconds after the start of each maneuver, x-channel and z-channel separations reached steady-state values that were biased approximately 5 feet and 10 feet, respectively, from the commanded values. The frequency response of the x-channel error was dominated by oscillations at 0.7 Hertz, though the response contained a great deal of high frequency noise. The VISTA aircrew did not experience abrupt longitudinal position changes of

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<sup>1</sup> Numerals preceded by an R within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

up to 2 feet several times a second, so the high frequency noise was most likely an artifact of the data link.

In one run (reference Figure 14d), x-channel separation had an uncommanded, abrupt ramp well into the steady-state response that represented an unreasonable acceleration. This was an example of the numerous data dropouts that resulted from the SADL limitations. The data dropouts typically caused abrupt ramps or jumps in separation distance, predominately in the x channel. The slopes of the ramps were due to the VISTA onboard position-smoothing algorithm which effectively prevented the data dropouts from being input to the controller as steps. As seen in the plots, the data dropout was smoothed into a manageable position error. The controller made corrections for these errors, and the formation maintained stability despite the data dropouts, but the errors corrupted position-keeping data. The quality of data received and the number of data dropouts was very sensitive to aircraft position and heading. Most runs had to be flown with the tail of the aircraft pointed towards the ground control station, placing an unnecessary restriction on flight testing and reducing the number of test points for which data was collected. A more robust data link would have increased the quantity and fidelity of the data collected. **Determine the position-keeping errors of the Automatic Formation Flight Controller with a more robust, all-aspect data link (R2).**

The frequency response of the z-channel separation was not consistent from run to run but was generally between 0.2 and 0.6 Hertz. The y-channel separation was characterized by relatively smooth, low-frequency oscillations independent of the other two axes. The amplitude of the y-channel separation varied from 3 to 8 feet with a frequency of 0.06 Hertz during the acceleration maneuvers. The maximum error for inertial separation was 65.3 feet, driven by the aforementioned ramp in x-channel separation from data-dropout effects.

All data plots from both accelerations are depicted in Figure 14 and Figure 15 in Appendix E. The error metrics for these maneuvers are summarized in Table 1.

#### **Lead Climb (Event 3A)**

All the climbs were accomplished with the lead maneuvering while VISTA was commanded to the standard position. The lead increased its altitude by 100 feet in approximately 15 to 20 seconds, yielding an average Rate of Climb (ROC) of about 5 to 7 feet/second.

The response of the controller was unique for each climbing maneuver performed. However, some characteristics were found in all repetitions. As the virtual lead aircraft initiated its climb, the controller exhibited a slight delay in its response. Despite the fact that the set-up conditions were not perfectly stable, the value of this parameter was normally less than 1 second and never exceeded 2 seconds. The delay caused VISTA to lag lead's climb, resulting in an altitude error of up to 10 feet during the first few seconds of the maneuver. Eventually the controller would command an adequate ROC, which caused the VISTA to match and overshoot the lead vertical position at approximately 7 seconds into the maneuver (a value confirmed in all the repetitions). The VISTA was able to catch up to lead and match the leader's altitude approximately halfway through the 100-foot climb. The controller required one overshoot before matching lead's ROC. The overshoot amplitude was usually less than 15 feet. Unfortunately, before the described dynamic could fully settle to a stable state, the lead,

approaching the commanded target altitude, would begin the level-off. The controller exhibited the opposite level-off dynamics, climbing slightly above the desired altitude, but with a magnitude very similar to the lag at climb entry. The controller lag caused the VISTA to keep climbing 1 to 2 seconds after the lead aircraft began to level off. Due to the short climbing time, 15 to 20 seconds, the two dynamics exhibited at the beginning and end of the climb were always overlapped and did not always allow a pure analysis of the climbing maneuver. **Repeat the climbing maneuvers with a greater altitude change by the lead aircraft (R3).** Once the lead had completed the level-off, the VISTA settled to within 3 feet of lead's altitude by 10 seconds. Some overshoots were notice during the transient phase, but their amplitude never exceeded 5 feet.

In most of the cases, the response in the x-channel separation was oscillatory, with a superimposition of modes characterized by different frequencies and amplitudes. The most predominant mode had a period of about 10 seconds and an amplitude that varied for each repetition. The damping ratio and the number of overshoots for the x-channel separation also varied for each repetition. The x channel exhibited one of two responses: either a large drifting x-channel error, or an oscillation of high frequency within approximately 10 feet from the commanded position. When the x-channel error was drifting, it would be the most significant error and would be the largest contributor to the total separation error.

The y-channel separation exhibited an oscillatory response as well. In most of the repetitions, the response was characterized by a lightly damped oscillatory mode with a period of about 20 seconds and an amplitude that varied for each repetition. Finally, the z-channel separation, already analyzed in detail, exhibited the most stable and predictable response and damped to an error of less than 5 feet.

All data plots from climbing maneuvers are depicted in Figure 6 through Figure 10 in Appendix E. The error metrics for these maneuvers are summarized in Table 1.

### **Lead Descent (Event 3B)**

All the descents were accomplished with the lead maneuvering while the VISTA was commanded to the standard position. The lead decreased its altitude of 100 feet in about 20 seconds, with an average Rate of Descent (ROD) of about 5 feet/second. The response of the controller was fairly consistent for all the repetitions accomplished. The dynamics observed were remarkably similar to those of the climbing maneuvers, but with opposite signs. The controller exhibited less than one second of delay after the lead began a descent. Because of this, the VISTA started its descent slightly after the lead and, consequently, generated an altitude error of about 5 feet in the first few seconds of the maneuver. The dynamics were similar to those already described for the climb maneuvers, but, in general, the descent maneuvers were characterized by smaller errors and shorter delays in the controller response.

After the previously observed reaction time, the controller commanded an adequate ROD, which caused the VISTA to overshoot the lead vertical position about 7 seconds into the descent. The controller would overshoot the lead position only once during a descending maneuver before matching the lead's ROD. The overshoot amplitude was less than 10 feet for

all of the repetitions. The controller delay caused VISTA to keep descending for about 1 second after the lead began its level-off.

Although the duration of the descents was slightly longer than the climbing maneuvers, the level-offs were still too soon to allow the aircraft dynamics to fully settle. **Repeat the descending maneuvers with a greater altitude change by the lead aircraft (R4).** Once the lead completed the level-off, VISTA would match altitude to within 3 feet in about 10 seconds. At least one overshoot was noted during the level-off phase of the maneuvers, with a high frequency correction to the commanded position after maneuver completion.

In most cases, the response in the x channel was oscillatory, with a superposition of different high- and low-frequency modes. Two modes were most commonly exhibited. The first was characterized by a low frequency period of approximately 10 seconds with an amplitude of about 5 feet and a low damping ratio. The second frequency exhibited a higher frequency oscillation with a period of approximately 1.2 seconds, a small amplitude of 1 foot, and a low damping ratio of .4 to .5. The y-channel separation also exhibited an oscillatory response. The specific parameters of the modes were slightly different for each repetition making it impossible to determine a trend in the results. Finally, the z-channel, previously analyzed above, exhibited the most stable and predictable response, and the error was usually corrected to less than 10 feet.

All data plots from descending maneuvers are depicted in Figure 11 through Figure 13 in Appendix E. Their error metrics are summarized in Table 1.

#### **Lead Turns (Events 5A through 5F)**

All turning maneuvers were accomplished while VISTA was commanded to the standard position. A build-up approach was taken to the heading change maneuvers, helping to identify trends in the controller performance. Turns were built up from 10-degree to 20- and 30-degree heading changes during a single data run. The drawback was that the y-channel separation was found to be slow to settle. In some cases when it was time to command the 30-degree turns, there was not enough airspace to allow the y-channel separation to settle from the previous maneuver.

The DSix-generated virtual lead flew in a windless environment in the ground simulation. VISTA, on the other hand, flew in an actual air mass with winds. Even though VISTA inertial velocity from the aircraft's Inertial Navigation Unit (INU) was input to the AFFC, the data showed persistent velocity errors dependent on aircraft heading. The source of these errors was not determined. As a result of the velocity errors, when the aircraft was turned off of the heading that minimized them, the x-channel separation would begin to drift. Consequently, the y-channel separation was not allowed to fully settle, as the x-channel separation would have drifted to the point where valid controller data was questionable. Plots from a multiple-turns maneuver run are presented in Figure 23 in Appendix E.

In general, the controller attempted to command the aircraft back to the desired position in all three channels during turns as long as the heading was commanded to within approximately 20 degrees of the heading for minimum velocity error. When outside of 20 degrees from this heading, the x-channel separation would begin an unbounded drift either

forward or aft from the commanded position. This was apparent in Figure 23 at 150 seconds when the lead heading angle was approximately -22 degrees and the controller allowed the VISTA to start drifting forward. This is again seen at 240 seconds when the lead aircraft heading angle was 28 degrees, and the controller allowed the VISTA to start drifting aft from the commanded position.

Referring to the altitude trace on Figure 23b, a dip in altitude is noted from the VISTA aircraft whenever a turn is begun to the left. Peaks can also be seen when a turn is begun to the right. These dips and peaks are due to the fact that the commanded standard position would put VISTA along the lead aircraft's wing line, such that during any turns when the lead aircraft was banked, the VISTA would have to maintain a lower or higher altitude to maintain the commanded position. The effect of data dropouts can also be seen in the plots of Figure 23. Significant data dropouts occurred on three different occasions: 145, 160, and 225 seconds. It is also clear from the above plots that when the x-channel error was allowed to grow to a large value (approximately 125 feet, as seen at 270 seconds), the other channels also began to display large errors as a result of the coupling effect of the axes system. This was the main reason to maneuver on or near the heading for minimum velocity error.

The x channel was the most aggressive to maneuver when VISTA was close to the commanded position. Three distinct frequencies are noted in the x-channel response. The first was a high frequency oscillation of approximately 4 Hertz with an amplitude of approximately 1 foot and is attributed to the positional and velocity noise of the system. The second oscillation had a period of approximately 2 seconds and an amplitude of approximately 4 feet, which appeared to be a result of continuous fore and aft throttle movements and could be observed in the aircraft. Finally, a low frequency oscillation with a period of approximately 10 seconds was noted. This oscillation seemed to allow the aircraft to drift approximately 10 feet away from the commanded position and then correct back to the commanded position again and again. As previously discussed, the overall trend of the x channel was a correction back to the commanded position unless the lead aircraft maneuvered to a heading greater than 20 degrees from the heading for minimum velocity error. Whether the controller drove the aircraft towards or away from the commanded position after a heading change depended on the resultant velocity errors. The magnitude and sign of the velocity errors, in turn, depended on VISTA heading relative to the heading that minimized them.

The y-channel separation displayed a low-frequency, lightly damped response to any lateral displacements that either developed from maneuvering or were as a result of data drop outs. The period of the oscillation in y-channel separation was approximately 20 seconds with a damping ratio of less than 0.1. The controller was unable to maintain a steady-state y-channel separation while the lead aircraft was in a turn. This was due to a continuous drift into or away from the leader depending upon whether the leader turned into or away from VISTA, respectively. Upon rollout, the y channel displayed the same long-period, lightly damped oscillation previously discussed, as it attempted to correct back to the commanded position. The y-channel errors were less than 30 feet for all maneuvering unless the x-channel error grew to large values.

The z-channel separation displayed the most stable response of all three channels. It would initially be displaced by lead bank angle at the beginning of turns as a result of the way the control system's axes were defined. During rollout, a z-channel error would develop in the opposite direction, again as a result of the axes. The maximum errors during 10-, 20-, and 30-degree heading changes were approximately 20, 28, and 38 feet respectively. The controller would fix these errors upon rollout with a 90% settling time of approximately 12 seconds, defined as the amount of time required for the separation to damp to within  $\pm 10\%$  of the commanded position change.

All data plots from turning maneuvers are depicted in Figure 16 through Figure 24 in Appendix E. Their error metrics are summarized in Table 1.

### **VISTA Position Changes with Lead Straight-and-Level**

#### **VISTA Vertical Position Changes (Events 15A, 15B, 17A, and 17B)**

All vertical position changes were conducted starting from the standard position and consisted of commanding the VISTA to climb or descend 30 feet while the lead was holding straight, level, unaccelerated flight. Two different sets of vertical position changes were performed. In the first set (15A and 15B), VISTA was commanded to climb 30 ft and subsequently descend back to the standard position. In the second set (17A and 17B), the sequence was inverted, and VISTA was first commanded to descend 30 ft and subsequently climb back to the standard position. The commanded position change was modeled as an instantaneous step input.

Overall the vertical position changes were effective and controlled in all three axes. The exhibited errors were minimal, particularly in the z channel, despite the fact that all of the step input errors, as a result of the position change, were in this channel. The largest errors recorded were caused by unstable setup conditions.

Once the position change was commanded, the controller always responded within 1 to 2 seconds. In most cases, the response was characterized by a second-order mode. The commanded value was overshoot for the first time approximately 5 seconds after the input. The amplitude of the first overshoot was less than 10 feet. The commanded vertical position was stable and kept within 3 feet of the commanded value after a total of 3 overshoots and an oscillation period of 15 seconds. The damping ratio was slightly different in each repetition, but was estimated to be at least 0.4.

The vertical position change maneuvers are presented in Appendix E in Figure 40 through Figure 42, Figure 47, and Figure 48. From these traces, it is evident that the x-channel separation was not affected by position changes in the z direction. The y-channel separation displayed a high frequency bobbling superimposed on the normal low frequency oscillations, whenever the aircraft was maneuvering in the z direction. The bobbling did not appear to alter the overall corrections of the controller. The error metrics for vertical position changes are summarized in Table 2, while their dynamic parameters can be found in Table 3.

### **VISTA Lateral Position Changes (Events 14A, 14B, 18A, and 18B)**

The first set of lateral position changes were commanded from standard position to a position of 0 feet in the y direction, or, in other words, a right position change of 30 feet to place the VISTA directly behind the lead aircraft. The aircraft was then commanded 30 feet to the left, back into the standard position. The results of these maneuvers are best illustrated in Figure 36 through Figure 39 in Appendix E.

Overall lateral position changes were effective and controlled in all three axes. From the Figure 38d plot, it is apparent that the characteristic shape of the x-channel response was unaffected by the lateral position change. The y-channel separation displayed the same long-period, low-damped oscillations seen previously when trying to correct errors. The period of the response was again found to be approximately 20 seconds and the damping ratio was less than 0.1. Specifically, in Figure 38e it is clear that there is a steady-state offset of approximately 5 feet to which the y channel appears to be settling. This steady-state offset was seen in varying degrees for all of the maneuver runs. The y-channel offset was an expected result, as VISTA flew in an actual air mass with winds, while the virtual lead was simulated in a windless environment, creating a crosswind error in the controller. As presented in Table 3 below, the initial overshoots of the commanded position were approximately 25 feet which occurred approximately 12 seconds after the 30-foot step positions were command. The 100% rise times (see Table 3), defined as the points at which separation distances first reached their respective commanded values, were approximately 6 seconds. 90% settling times were approximately 80 seconds after the command.

The z-channel errors showed a disturbance whenever a displacement in the y channel was commanded. This was an expected result, as the controller would command VISTA to bank in order to effect the position change. Due to the axis-setup of the control system, any changes in bank would trade y-channel separation for z-channel separation when there was an offset in the y direction. These disturbances in the z channel were damped and were not greater than 10 feet for the position change to trail or back out to standard formation.

The characteristics of the 60-foot position changes (Figure 49 and Figure 50, Appendix E) are presented in Table 2 and Table 3 and do not show a significant difference when compared to the 30-foot step commands, except for the proportionally larger overshoot of 58 feet and an increased 100% rise time of 9 seconds. Settling time, damping, and the period remained relatively unchanged. The x-channel ramp at approximately 105 seconds (Figure 49d) is due to a data drop out, which is quickly corrected when good data are received again.

The final notable result during the lateral position change maneuvers was the large initial overshoot for both the 30-foot and 60-foot cases. This result was expected and was due to the proportional error limits placed on the control laws, such that the system would be significantly more damped when the error decreased to less than 20 feet.

### **VISTA Forward Position Changes (Events 16A and 19A)**

Starting in stable flight with the VISTA in the standard formation position, a commanded formation change to line abreast position required the VISTA to accelerate and move forward 30 feet. The lead aircraft remained in straight, level, unaccelerated flight throughout the position

change. Two runs were accomplished and compared for the position change of 30 feet. The AFFC commanded a slight increase in velocity to draw alongside lead, then overshoot the desired position by up to 10 feet as it attempted to slow and correct the residual x-channel separation errors. The data plots for the 30 foot position change are shown in Figure 43 and Figure 44.

Maximum x-channel separation error was 31 feet, due to the initial 30-foot step input to command the position change. The y-channel separation was characterized by a smooth, low-frequency response that depended greatly on its initial value. In one case, the error ramped slowly to zero, while in another case the error oscillated at 0.04 Hertz with amplitude of 35 feet due to existing error when the maneuver began. This was an expected response of the controller algorithm due to an initial error offset. The z-channel separation stayed within 6 feet, exhibiting small transients when the VISTA accelerated. The maximum error for total separation in the most representative maneuver was 30.5 feet.

A similar forward position change of 60 feet was commanded with the VISTA initially in standard formation position with the lead aircraft. Rather than ending in line abreast formation, the VISTA accelerated to a position 30 feet in front and 30 feet to the left of the lead aircraft – in other words, a reverse formation. One run was accomplished for this maneuver, as depicted in Figure 51. Doubling the distance for the VISTA to travel did not seem to affect the overall outcome of the maneuver, other than increase the time required to accelerate to and stabilize on the new position. The parameters for this maneuver are compared to the 30-foot forward position change in Table 3 below.

#### **VISTA Aft Position Changes (Events 16B and 19B)**

Starting in line abreast position, the commanded formation change to standard position required the VISTA to decelerate and move aft 30 feet. Two runs were accomplished and compared. In one case, the VISTA successfully commanded a slight decrease in velocity to drop back from the lead aircraft. The data plots for this case are presented in Figure 46. The x-channel separation response exhibited two frequencies, with a low-frequency component at 0.1 Hertz and a second component at 0.7 Hertz. The y-channel separation was a gradual, 0.07-Hertz oscillation around the commanded value with less than 5 feet of error throughout the maneuver. The z-channel separation response was less predictable, and could have been affected by the deceleration and/or wind buffet. The most recognizable frequency response in z-channel separation was a component at 0.4 Hertz. Total separation error was driven by the commanded position change, but did not exceed 12 feet at any point in the maneuver.

The second position change case was indicative of the difficulties the AFFC algorithm had with deceleration maneuvers. The VISTA failed to perform the position change, with x-channel separation oscillating around a constant steady-state bias. The data plots for this case are presented in Figure 45. As in the first case, the x-channel separation response contained a low-frequency component at 0.1 Hertz and a second component at 0.7 Hertz, but was markedly different due to the presence of high frequency noise. The y-channel and z-channel separation responses were similar to the first case, at 0.05 Hertz and 0.5 Hertz respectively. The most unusual aspect of this maneuver was that the VISTA did not respond at all to the commanded position change. The presence of a noisy signal, as well as the lack of response, may indicate

that a data dropout just prior to the maneuver placed the VISTA in dead-reckoning mode, in which case the VISTA was following the last known condition of the lead aircraft.

All data plots from both aft position change maneuvers can be found in Figure 45, Figure 46, and Figure 52 in Appendix E. The dynamic response parameters for both maneuvers are summarized in Table 3 below, and the error metrics are summarized in Table 3.

### **Lead Combination Maneuvers with VISTA in Standard Position**

#### **Lead Climb and Acceleration (Event 6A)**

In this maneuver (reference Figure 25 and Figure 26, Appendix E), the lead aircraft simultaneously climbed 100 feet and accelerated 50 knots. The VISTA was commanded to the standard position throughout the maneuver. Two runs were compared and showed similar results. The x-channel separation (and associated error) demonstrated variant frequencies, the dominant of which was at about 0.7 Hertz. The commanded position was maintained within about 10 feet during most of the maneuver, and maximum x-channel error was less than 15 feet for both runs. A data dropout occurred about halfway through its completion followed by a fast (less than 3-second) recovery back to the commanded x-channel position. The y-channel separation was sinusoidal and dominated by a smooth, lightly damped, low-frequency response, though a 0.6-Hertz, low-amplitude oscillation appeared to be superimposed. The y-channel separation oscillated about errors of approximately 12 feet and 5 feet for the two maneuvers, rather than about the commanded position. Maximum y-channel errors were 10 feet and 20 feet for the two runs. The z-channel separation showed that the VISTA initially lagged the lead aircraft's climb by about 10 feet initially, overshoot the commanded position by 20 feet, and then slowly converged to the commanded position over the subsequent 20 to 30 seconds. Maximum z-channel error was less than 20 feet for both runs. Finally, maximum total separation was within 13 feet for both runs.

#### **Lead Descent and Acceleration (Event 7A)**

In this maneuver (reference Figure 27, Appendix E), the lead aircraft simultaneously descended 100 feet and accelerated 50 knots. The VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. The high frequency oscillations in the x-channel separation were an artifact of the data link, and the maximum x-channel error was kept to within approximately 10 feet. The corrections in the y-channel appeared smooth, with a very low frequency oscillation keeping the separation error within 10 feet for the majority of the maneuver. The z-channel error oscillated about a magnitude of approximately 10 feet, and maximum z-channel error was kept below 15 feet. Finally, total separation was dominated by x-channel error and showed similar trends. Maximum total separation error was just under 15 feet during the maneuver.

#### **Lead Climb and Left Turn (Event 8A)**

In this maneuver (reference Figure 28, Appendix E), the lead aircraft simultaneously climbed 100 feet and turned left for a 30-degree heading change. The VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. The airspeed error, negligible at the start of the run, subsequently increased to about 3 feet/second during the execution of the maneuver. This velocity error translated into an x-

channel separation that initially held within 10 feet but then diverged to greater than 50 feet upon completion of the event. Again, the x-channel separation showed a relatively high frequency oscillation, probably due to the controller's abrupt throttle inputs. The y-channel separation, on the other hand, was smooth again, demonstrating a lightly damped, low-frequency, oscillatory response with a maximum error of about 25 feet. The z-channel separation and error showed trends similar to other climbing maneuvers: the VISTA initially lagged lead's climb with an error of about 40 feet, followed by an overshooting correction of about 20 feet of error, and culminating with a smooth, damped convergence about the commanded position. The total separation was dominated by the z-channel error at the start of the climb, and by the x-channel error once the z-channel error damped out and the x-channel separation diverged. Maximum total separation error was approximately 37 feet and occurred at the end of the maneuver.

#### **Lead Descent and Right Turn (Event 8B)**

In this maneuver (reference Figure 29, Appendix E), the lead aircraft simultaneously descended 100 feet and turned right for a 30-degree heading change. The VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. The maneuver began with a 25-foot error in the x-channel which grew to 50 feet before correcting to zero by the end of the maneuver. The large x-channel error was probably due to a velocity error that was about 3 feet/second at the start of the maneuver and subsequently decreased to zero as the maneuver progressed. The y-channel separation demonstrated lightly damped, low-frequency oscillations centered about an error of approximately 10 feet with a maximum error 21 feet. The z-channel error during turn entry and rollout was probably due to y-channel separation transforming to z-channel separation as the VISTA changed angle of bank. This is supported by the plot of total inertial separation, which shows inertial separation dominated by x-channel separation. Maximum z-channel error was 27 feet. Maximum total separation error was about 52 feet.

#### **Lead Acceleration and Left Turn (Event 9A)**

In this maneuver (reference Figure 30 and Figure 31, Appendix E), the lead aircraft simultaneously accelerated 50 knots and turned left for a 30-degree heading change. The VISTA was commanded to the standard position throughout the maneuver. Two runs of this maneuver type were evaluated, both showing similar results. As with previous turning maneuvers, the velocity error increased to about 3 feet/second during the course of the maneuver, causing the x-channel error to diverge to an average of 113 feet at the end of the maneuver. The y-channel separation demonstrated lightly damped, low-frequency oscillations centered with an average maximum error of 26 feet and appearing to converge to zero error in both runs. Trends in z-channel separation were similar for both runs and showed a maximum error of about 25 feet. However, one run appeared to show the coupling between the y- and z-channels that was first described for Event 8B above. This assessment seems to be confirmed by the plot of total separation, which is dominated by the x-channel separation and shows no increase in magnitude with the jump in z-channel error at the beginning of the maneuver. Maximum total separation error was 104 feet at the end of the maneuver.

#### **Lead Climb, Acceleration, and Left Turn (Event 10A)**

In this maneuver (reference Figure 32, Appendix E), the lead aircraft simultaneously climbed 100 feet, accelerated 50 knots, and turned left for a 30-degree heading change. The

VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. As with previous turning maneuvers, the velocity error increased during the course of the maneuver, though the x-channel error remained within 26 feet and did not diverge. The y-channel separation at the beginning of the maneuver was about 10 feet, and y-channel error increased to about 40 feet during the maneuver before converging to zero. A plot of y-channel separation shows the VISTA apparently lagging lead's turn, causing the virtual lead to fly in front of the VISTA during the left turn. A plot of z-channel separation appears to show the VISTA lagging the initial climb, followed by an overshooting correction and maximum z-channel error of 24 feet. Maximum total separation error was less than 8 feet during the course of the maneuver, probably due to the slow y-channel response countering the increased separation in the x- and z-channels.

#### **Lead Climb, Acceleration, and Right Turn (Event 12A)**

In this maneuver (reference Figure 33, Appendix E), the lead aircraft simultaneously climbed 100 feet, accelerated 50 knots, and turned right for a 30-degree heading change. The VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. The velocity error increased to about 3 feet/second during the course of the maneuver, causing the x-channel error to diverge to 177 feet by the end of the maneuver. The y-channel separation demonstrated lightly damped, low-frequency oscillations centered fairly close to the commanded position with a maximum error 12 feet. The average of the y-channel oscillations appeared to diverge slightly during the maneuver, however, probably due to the divergent x-channel error transforming to y-channel error during the turn. The z-channel separation was slightly oscillatory and had an average error of about 10 feet near the start of the maneuver, converging to the commanding position by the end of the run. However, once again, the initial z-channel error was probably due to y-channel separation transforming to z-channel separation at the beginning of the turn. This is confirmed by the plot of total separation, which appears to be dominated by x-channel error.

#### **Lead Descent, Acceleration, and Right Turn (Event 12B)**

In this maneuver (reference Figure 34, Appendix E), the lead aircraft simultaneously descended 100 feet, accelerated 50 knots, and turned right for a 30-degree heading change. The VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. As with most of the turning maneuvers, airspeed error increased to about 2 feet/second during the course of the maneuver and caused the x-channel error to diverge to 82 feet by the end of the maneuver. The y-channel separation demonstrated lightly damped, low-frequency oscillations centered fairly close to the commanded position with a maximum error of only 11 feet. The z-channel separation also oscillated about the commanded position with a maximum error of 21 feet. The initial increase in z-channel error was probably due to y-channel separation transforming to z-channel separation at the beginning of the turn. This is confirmed by the plot of total separation, which appears to be dominated by x-channel error and shows no apparent spike in inertial error during the initial increase in z-channel error. Maximum total separation error was about 75 feet and occurred at the end of the maneuver.

#### **Lead Descent, Acceleration, and Left Turn (Event 13B)**

In this maneuver (reference Figure 35, Appendix E), the lead aircraft simultaneously descended 100 feet, accelerated 50 knots, and turned left for a 30-degree heading change. The

VISTA was commanded to the standard position throughout the maneuver. One run of this maneuver type was evaluated. The velocity error increased to about 3 feet/second during the course of the maneuver, causing the x-channel error to diverge to 50 feet at the end of the maneuver. The y-channel separation demonstrated lightly damped, low-frequency oscillations centered fairly close to the commanded position with a maximum error 56 feet after about 25 degrees of turn. As with the left turn in Event 10A, the virtual lead flew in front of the VISTA during the turn. The z-channel separation showed coupling with the y-channel separation at the start of the turn, followed by an overshooting correction and a large magnitude, low frequency oscillation about the commanded position. Maximum z-channel error was about 35 feet and occurred approximately 5 seconds prior to lead's level-off. Total separation was dominated by x-channel error. However, it appeared to be shifted down in magnitude due to the y-channel separation, which was lower in magnitude than commanded. Maximum total separation error was 46 feet and occurred at the end of the maneuver.

## Maneuver Summary

**Table 1 – Maximum Errors for Formation Maneuvers**

Event	Sortie	Record	Maximum Error				
			x (feet)	y (feet)	z (feet)	Velocity (feet/second)	Inertial Sep (feet)
3A	1	4	11.0	19.4	15.0	3.1	19.2
3A	3	4	107.0**	11.0	18.6	12.8	38.8
3A	5	1	12.2	23.9	14.1	2.5	24.8
3A	5	3	77.1 *	4.4	13.1	3.2	69.2
3A	5	5	11.1	5.9	14.8	3.0	4.3
3B	3	4	166.2 *	56.9	9.8	3.2	96.4 *
3B	1	5	12.0	18.5	10.5	2.9	20.1
3B	5	2	7.1	9.9	7.8	1.8	10.4
4A	1	6	69.1*	17.5	12.5	2.9	65.3
4A	5	5	8.1	2.7	16.1	4.1	5.4
5A	1	8	33.5	31.4	20.7	4.5	29.5
5A	4	1	67.4**	38.6	25.9	3.7	59**
5A-5F	3	12	106.8**	80.9	56.5	3.8	102.6**
5B	1	10	76.7**	24.7	32.9	3.7	66.6**
5D, 5B, 5F	4	3	246.2 *	57.5	38.8	2.9	236.2 *
5C	1	3	105.3**	50.8	27.7	10.2	50.9**
5C	1	13	92.0*	132.5	61.4	3.1	125.4*
5E	1	11	160.8**	16.5	22.9	3.3	151.9**
5F	1	14	37.0	366.5	75.2	3.1	358.3

\* error caused by data dropouts

\*\* x-channel divergence due to system velocity errors

The results for in-flight position-keeping error of the AFFC algorithm (Table 1) indicated that it was capable of maintaining formation flight with the lead aircraft. Three external factors played key roles in determining the success of each engagement, as well as the degree of precision with which the algorithm maintained formation: the quality of the data link, the formation's ability to head perpendicular to the wind, and the presence of errors during initialization. When all three of these factors were favorable, the algorithm had precise response in the z channel; precise response to acceleration in the x channel, up to the throttle limit; and a low-frequency, lightly damped response in the y channel. Even under favorable conditions, the algorithm was not capable of decelerating in formation, due to the issues discussed in the limitations section.

**Table 2 – Maximum Errors for Position Change Maneuvers**

Event	Sortie	Record	Maximum Error				
			x (feet)	y (feet)	z (feet)	Velocity (feet/second)	Inertial Sep (feet)
14A	1	16	28.2	37.4	4.9	3.2	45.9
14B	1	21	9.6	33.0	6.0	2.5	29.7
14A & B	3	13	13.2	41.2	32.1	2.7	13.3
14A & B	4	3	117.5 *	37.2	6.6	3.5	105.5 *
15A & B	3	13	13.1	13.5	32.1	2.6	12.7
16A	1	1	31	30.5	48.6	5.5	3.0
16A	2	3	14	31.0	5.8	6.4	2.9
16B	1	1	32	44.0	19.0	4.9	2.9
16B	2	3	14	32.0	4.5	6.5	4.5
17A	2	5	72.8	9.7	12.3	3.4	8.9
17B	1	34	71.0	7.6	33.3	2.8	4.4
17A & B	3	14	12.5	6.4	32.1	2.9	8.5
18A & B	3	16	129.3 *	75.6	9.5	2.9	120.3 *
18A & B	4	15	12.9	67.8	6.6	2.7	41.5
19A	1	4	6	86.6	17.0	7.4	3.1
19B	1	4	6	64.8	14.6	6.4	2.8

When data link quality was unfavorable, high-frequency noise became apparent in the x-channel separation response. As link quality further deteriorated, the VISTA entered dead-reckoning mode and the algorithm would fly formation off the lead aircraft's last known velocity vector. With no data link, the algorithm would not initialize. When formation heading was unfavorable and/or errors were present in the initial conditions, the algorithm reached equilibrium with non-zero steady state z-channel error, non-zero steady state or divergent x-channel error, and larger amplitude y-channel oscillations.

**Table 3 – Dynamic Parameters for Position Change Maneuvers**

Position Change	Overshoot Distance (feet)	Rise Time 100% (Sec)	Damp Ratio	Period of Oscillation (sec)	Settling Time 90% (sec)
Climb/Descend 30 feet	10	5	0.4	15	15
Descend/Climb 30 feet	8	4	0.5	12	12
Lateral 30 feet	25	6	<0.1	20	80
Lateral 60 feet	58	9	<0.1	20	80
Forward 30 feet	2	8	0.7	1.3	8
Forward 60 feet	0	16	0.7	1.4	14
Aft 30 feet	3	19	0.7	9, 1.3	18
Aft 60 feet	1	62	0.7	10, 1.4	58

### **Qualitative Assessment of AFFC-Controlled Aircraft Maneuvers**

Pilot comments and ratings were based on the Pilot Post-Flight AFFC Questionnaire. Pilot ratings are presented as histograms in Appendix B, along with the questionnaire. Questions focused on three key aspects of the AFFC: (1) ease of engagement, (2) aircraft motions and stability during lead maneuvers and position changes, and (3) system disengagement. Most of the questions included pilot rating scales, though the pilot comments best supported the test objective. Histograms summarizing pilot ratings are also given in Appendix B. Pilot #1, an AV-8B pilot with approximately 1100 flight hours, flew the first, second, and fifth data flights. Pilot #2, an F-15E pilot with approximately 1500 flight hours, designed the control algorithms and flew the third and fourth data flights.

Ease of engagement (reference Question 1, Appendix B) was rated between moderately easy to moderately difficult with the exception of one flight, discussed later. The required technique was to initially engage the controller in the y and z channels only, manually adjusting the throttle to maneuver the aircraft forward or aft into the commanded position. When the aircraft was within approximately 10 feet of the commanded x-channel position, the throttle control was also engaged. Additionally, the previously discussed velocity errors depended on aircraft heading, making full initialization of the system difficult until the heading for minimum velocity error was determined. Being off of this heading would result in a poor engagement in which the VISTA would never stabilize in the commanded x-position and slowly drift either forward or aft. When the drift was recognized by the pilot, a heading change was commanded to the lead aircraft by the ground station causing the VISTA to follow to the new heading. Eventually this series of adjustments would lead to a heading where the x channel would drive to the desired position. This would then be the heading for minimum velocity error from which all tests would start. If the lead heading was commanded to a heading beyond the heading for minimum velocity error, the aircrew would observe a divergence in the x-channel error. Another obstacle to successful initializations was that the quality of the SADL connection was dependent on the VISTA's position and heading, further increasing pilot workload. On a particular data

flight, ease of engagement was rated "extremely difficult", as the SADL connection was always poor, regardless of the VISTA's position or heading.

Aircraft motions during engagement (reference Question 2, Appendix B) were predictable in the y- and z-channels. However, x-channel error was unpredictable until a heading was found that minimized velocity errors. Within approximately 10 feet of the commanded x position and with the AFFC engaged in all axes, throttle control was positive and timely. During some engagements, especially those with multiple data dropouts, the throttle control would become very erratic, producing large-amplitude, damped oscillations in x-channel separation. Engagement with a significant crosswind would produce slow, lightly damped oscillations in y-channel separation.

Once the VISTA was holding the commanded position prior to lead maneuvering (reference Question 3, Appendix B), aircraft motions were smooth. Control in the z channel was in all cases precise and well damped. The y channel sometimes had slow, lightly damped oscillations that were noticeable but not objectionable. Occasionally the y-channel separation would allow a steady-state error offset from the desired lateral position. Finally, the x-channel error would slowly diverge if the VISTA was not on a heading that minimized crosswind effects. Aircraft motions were also assessed to be smooth during lead maneuvering (reference Question 4, Appendix B).

There was a noticeable difference between AFFC control with the VISTA near the commanded position (inside approximately 10 feet) and with the VISTA out of position. In order to limit the effects of data dropouts and to prevent instabilities, the maximum error input to the controller was limited to 10 feet, 20 feet, and 20 feet in the x, y, and z channels, respectively. When the error in each channel was greater than its respective threshold, the proportional control in that channel would be set at a fixed value. For example, if the x-channel error was 100 feet, the controller would only "see" an error of 10 feet and would command a velocity change (through throttle inputs) commensurate with a 10-foot error. This had the effect of smoothing the controller outputs. Once the error was reduced to a value below the error limit, the controller would use normal proportional control. As a result, the controller outputs were much more positive and oscillatory with the aircraft near the commanded position.

The error-limiting described above explains some of the difference in subjective ratings given by the two pilots (reference Question 5, Appendix B). There was a definite learning curve during flight testing as the test team determined how to minimize the effects of winds aloft and to find ideal headings to initiate the maneuvers. Consequently, the VISTA was closer to the commanded position on the last few flights (with Pilot #2), more time was spent inside the error limits, and the controller outputs were more abrupt and oscillatory. Conversely, on the earliest flights, the VISTA was out of position (especially in the x channel) more often, and controller outputs were thus more damped.

During lead maneuvering (reference Question 5, Appendix B), the pitch axis was well damped and displayed no oscillations. The roll axis occasionally entered an undamped to lightly damped gentle oscillation that was very noticeable but not objectionable to the aircrew, and "slow enough not to get sick". The amount of throttle oscillations was very dependent on how

close the VISTA was to the commanded position. Within 10 feet of the commanded position, the controller made continuous throttle inputs, creating oscillations in x-channel error (reference Question 12, Appendix B). In fact, the presence of abrupt throttle surges was the best indication to the aircrew that the AFFC was positively trying to hold the VISTA in the commanded formation position. The oscillations generally started out large in magnitude but damped quickly to a low-amplitude oscillation about the commanded x-channel position. If the x-channel separation drifted outside of 10 feet from the commanded position, throttle inputs would diminish to the point of being imperceptibly small, and the aircraft would often stabilize well out of position with a high x-channel error. Finally, during turns off of the heading that minimized velocity errors, pitch and roll control were usually unaffected, but the x-channel error would diverge, depending on the magnitude of the headwind or tailwind component of the winds aloft. Turning back to the original heading usually allowed the AFFC to bring the VISTA back into the commanded position, even if x-channel errors had grown to hundreds of feet.

Formation position changes not accompanied by lead maneuvering were generally characterized by minor vertical overshoots less than 10 feet in magnitude (reference Question 6, Appendix B). Vertical corrections were neither too fast nor too slow. Laterally, the aircraft would sometimes grossly overshoot (greater than 20 feet), and the correction back to the commanded position was either slow or imperceptible. Finally, fore and aft control was aggressive when the position change was initiated while the VISTA was within 10 feet from the initial commanded position and on a heading that minimized velocity errors. However, the aircraft was slow to accelerate or decelerate to the new commanded position.

Combined maneuvers, in which multiple distinct maneuvers were performed simultaneously, demonstrated an additive effect of the individual maneuver dynamics (reference Question 7, Appendix B). As expected, there were no apparent interaction, or coupling, effects. For example, a climbing and accelerating turn demonstrated all of the positive and negative individual characteristics of a climb, acceleration, and turn. No uncomfortable or unexpected dynamics were encountered during combined maneuvers.

Regarding apparent stability of the individual control axes (reference Question 9, Appendix B), the z-axis invariably appeared to be the most stable. The most unstable axis depended on how close the aircraft was to the commanded position. When within approximately 10 feet of the commanded position, the AFFC positively held the aircraft in the x axis, but the oscillations in throttle inputs appeared to be near an instability. Indeed, on one early flight, the velocity gains were increased to assess their effect. Any increase in velocity gain ultimately drove the x-channel error into a divergent, large-amplitude, relatively high frequency oscillation. Moreover, during flight with the VISTA in or near the commanded position, the aft cockpit throttle appeared "nervous" and jittery, moving much quicker than the engine could respond. Finally, the y-channel error often entered low-magnitude, low frequency oscillations that were manifested with the aircraft both in and out of the commanded position. A coupling effect was noted, apparently due to the reference frame setup of the system, when a large x-axis error was allowed to develop. If greater than 700 feet out of position in the x channel, the y and z channels would begin a steady bounded oscillation of approximately 15 degrees in pitch and 15 degrees in bank. The motion during this out-of-position state was found to be uncomfortable (not suitable

for manned flight) and would surely cause a physiological incident given enough time. There was no coupling effect when the x-channel error was less than approximately 100 feet.

During all of the flight testing, the VISTA automatically disengaged the AFFC only once (reference Questions 10 and 11, Appendix B). On one particular flight, the aircraft INU failed, causing the AFFC attitude reference to tumble. The aircraft immediately entered what appeared to be an abrupt, full-deflection aileron roll to the left. The AFFC disengaged at about 135 degrees angle of bank due to the VSS Vehicle Integrity Monitor and disengagement logic. The event was unexpected and very objectionable to the aircrew. However, it did not represent a problem with the AFFC itself, but instead an anomaly with a separate aircraft system. The event highlighted that the AFFC was only as good as its inputs, and that a redundancy management system with redundant input sensors would be necessary in an operational formation controller.

Finally, though the aircrew could only directly assess the characteristics of the controller from inside the controlled aircraft, pilot judgment was used to assess the ease of flying manned formation off of the AFFC-controlled aircraft (reference Question 8, Appendix B). As most of the controller inputs were smooth, a manned aircraft could have flown formation off of the VISTA during the flight tests. However, the oscillations in the y-axis would have increased pilot workload considerably.

## **Qualitative Evaluation Summary**

Aircraft motions with the AFFC, when near the commanded formation position, were generally smooth and not objectionable. Continuous undamped or lightly damped oscillations in roll were noticeable but not uncomfortable for the aircrew. The most apparent oscillations were in the x-channel due to abrupt throttle inputs, causing the aircraft to intermittently surge forward. These were not objectionable and were the best indication that the controller was holding the aircraft in or near the commanded position. In fact, the controller probably erred on the "smooth" side, especially during formation position changes, as it usually corrected errors too slowly or allowed a steady-state formation error.

When at or near the commanded position, a human could easily and comfortably serve as a crewmember in an aircraft flying under the control of the AFFC. Additionally, the motions of the AFFC-controlled aircraft were smooth enough for a manned aircraft to follow in close formation. To be sure, roll oscillations would increase pilot workload. However, this test demonstrated that unmanned and manned aircraft could be integrated into a single flight.

Overall, the AFFC as tested was assessed to be **Satisfactory** for the mission of manned automatic formation flight. **Continue development of the Automatic Formation Flight Controller (R5).**

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## CONCLUSIONS & RECOMMENDATIONS

One test objective was to determine the in-flight position-keeping errors of the Automatic Formation Flight Controller (AFFC) algorithm. Maneuvers were designed to measure separation data during lead aircraft maneuvers, including turns, accelerations, decelerations, climbs, and descents. Unfortunately, during decelerating maneuvers, the lead aircraft slowed too quickly for the Variable Stability In-Flight Simulator Test Aircraft (VISTA) to stay in position, even with idle power. Thus the virtual lead aircraft dynamics did not support the determination of AFFC position-keeping errors for decelerating maneuvers.

**Determine position-keeping errors of the Automatic Formation Flight Controller during decelerating maneuvers with a virtual lead aircraft that decelerates at a rate slower than the controlled aircraft (R1, page 7).**

The Situation Awareness Data Link (SADL) used during flight test had two key limitations. First, the quality of the data link was very sensitive to aircraft heading, such that most runs had to be flown with the tail of the aircraft pointed towards the ground control station. This placed an unnecessary restriction on flight testing and reduced the number of test points for which data was collected. Second, the data link was characterized by numerous data dropouts, corrupting much of the data. A more robust data link that addresses these deficiencies would allow AFFC position-keeping errors to be determined with greater fidelity.

**Determine the position-keeping errors of the Automatic Formation Flight Controller with a more robust, all-aspect data link (R2, page 8).**

During all climbing maneuvers, VISTA initially lagged the lead aircraft, resulting in an altitude error of up to 10 feet. The controller was able to command the VISTA back to the desired formation position approximately halfway through the 100-foot climbs, matching lead's rate of climb within approximately one overshoot. However, the z-channel separation response was not allowed to damp to steady-state prior to the lead aircraft's level-off. As a result, the position-keeping dynamics during climbing maneuvers could not be fully analyzed.

**Repeat the climbing maneuvers with a greater altitude change by the lead aircraft (R3, page 9).**

Similarly, lead aircraft descents were limited to 100 feet. The z-channel separation was not allowed to damp to steady-state before level-off. Consequently, as during the climbing maneuvers, the position-keeping dynamics during descending maneuvers could not be fully analyzed.

**Repeat the descending maneuvers with a greater altitude change by the lead aircraft (R4, page 10).**

Finally, when in or near the commanded position, a human could easily and comfortably serve as a crewmember in an aircraft flying under the control of the AFFC. Additionally, the motions of the AFFC-controlled aircraft were smooth enough for a manned aircraft to follow in close formation, demonstrating the ability to integrate unmanned and manned aircraft into a single flight. Overall, the AFFC as tested was assessed to be **Satisfactory** for the mission of manned automatic formation flight

**Continue development of the Automatic Formation Flight Controller (R5, page 23).**

## REFERENCES

1. Morgan, Michael , *A Study in the Drag Reduction of Close Formation Flight Accounting for Trim Actuation and Dissimilar Formation*, Unpublished MS thesis work, AFIT/GAE/ENY/05M-05, School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH.
2. Test Pilot School 03B Test Management Project, SELF SERVE (Limited Evaluation Of Automated Aerial Refueling Algorithm), TPS-03B, Edwards Air Force Base CA, June 2003.
3. Osteros, Ryan K , *Full Capability Formation Flight Control*, Unpublished MS thesis work, AFIT/GAE/ENY/05M-05, School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH.
4. NF-16D 86-0048 Modification Flight Manual, WI-FARG-NF16D-0071-R05, 6 December 2002.

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## **Appendix A – Data Reduction and Analysis**

## Data Reduction and Analysis

The most important information the team required for accurate data reduction was the relative positions between the virtual leader and the VISTA trail aircraft while performing the planned maneuvers.

Since the order of magnitude of the distances that was evaluated was in the tens of feet, the virtual leader position and the VISTA position had to be known with a high level of precision. Therefore, in order to minimize transmission delay errors and coordinate conversion errors, the following procedure was used:

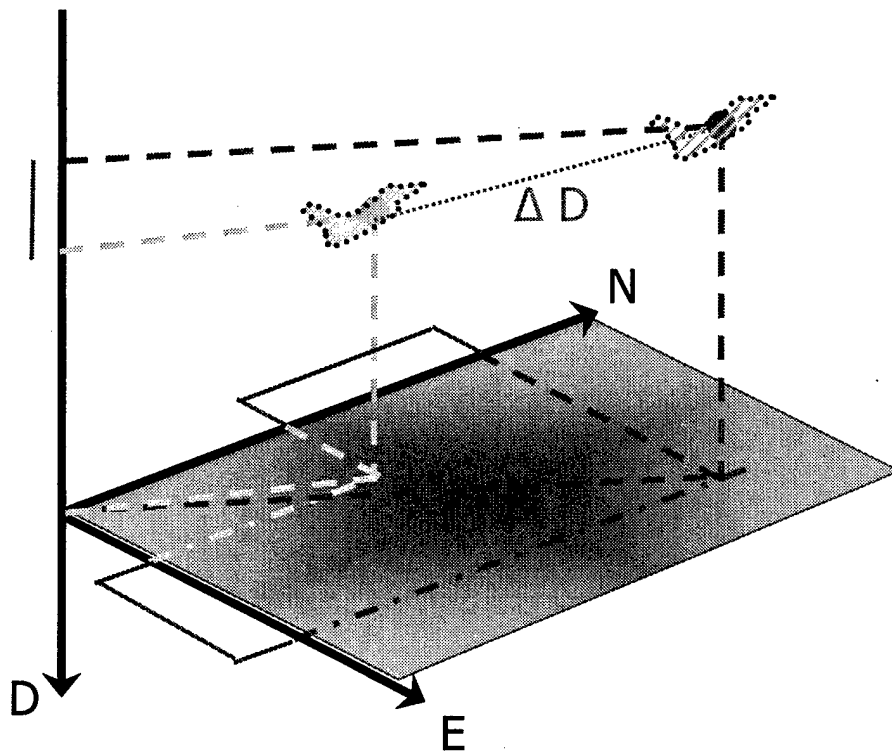
1. Virtual leader position ( $X_L, Y_L, Z_L$ ) and VISTA position (or wingman position,  $X_V, Y_V, Z_V$ ) were referenced from a North-East-Down (NED) reference system from a local origin, which was the end of runway 22, Edwards AFB, CA.
2. To avoid transmission time delays (and consequent relative position errors), the position of the virtual leader when it was received by the VISTA, regardless of transmission delays, was used as the lead position at the time of reception.
3. Virtual leader and VISTA positions were considered with the same reference time ( $t_R$ ), VISTA time.

For each maneuver flown, a time slice of interest was determined as  $T = [t_{in}, \dots, t_R, \dots, t_{fin}]$ . Then, for each sample, the following data were calculated and plotted for each maneuver run presented in Appendix E:

1. Lead-VISTA relative x-channel separation  $\Delta X(t_R) = (X_L, t_R) - (X_V, t_R)$
2. Lead-VISTA relative y-channel separation  $\Delta Y(t_R) = (Y_L, t_R) - (Y_V, t_R)$
3. Lead-VISTA relative z-channel separation  $\Delta Z = (Z_L, t_R) - (Z_V, t_R)$
4. Lead-VISTA relative total separation  $D(t_R) = \{\Delta X(t_R)^2 + \Delta Y(t_R)^2 + \Delta Z(t_R)^2\}^{1/2}$
5. Lead-VISTA Velocities
6. Lead and VISTA Heading Angles
7. Lead and VISTA Altitudes

The above separation distances (summarized in Figure 3) were transformed into the VISTA wind axis reference frame since this was the frame of reference the controller utilized in-flight. Finally, for each maneuver of interest, the curve of  $D(t_R)$  versus time ( $t_R \in T$ ) was plotted and the values of the relative distances  $\Delta X, \Delta Y, \Delta Z$  were plotted.

Data was saved for this analysis in text files and Matlab® format files.



**Figure 3 – NED Reference System and Relative Distances  $\Delta X$ ,  $\Delta Y$ ,  $\Delta Z$**

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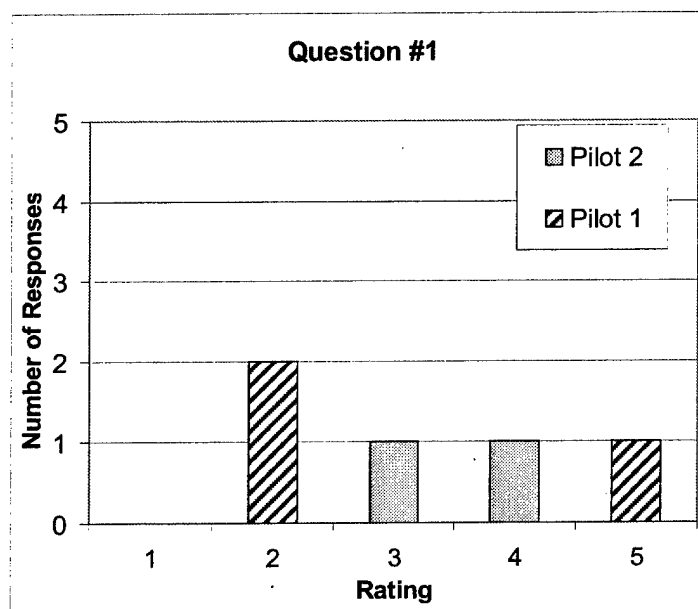
## **Appendix B – Post-Flight Questionnaire**

## Pilot Post-Flight AFFC Questionnaire

The following set of questions will be used to evaluate the AFFC system for usability in-flight as a manned formation flight controller, and to assess the impact of the automatic formation keeping flight inputs on other manned aircraft in the flight. Answers to these questions will be used to support Test Objective 2.

1. Rate and provide comments about the difficulty of the maneuvering required to get the aircraft in position prior to engagement.

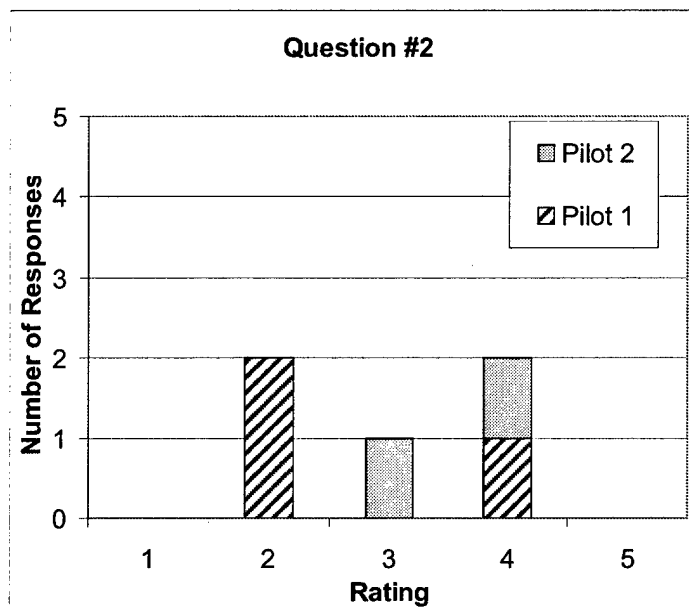
Extremely Easy – 1    2    3    4    5 – Extremely Difficult



Specific Comments: (See Results and Analyses section)

2. Rate and provide comments about the predictability of aircraft motions during engagements of the AFFC.

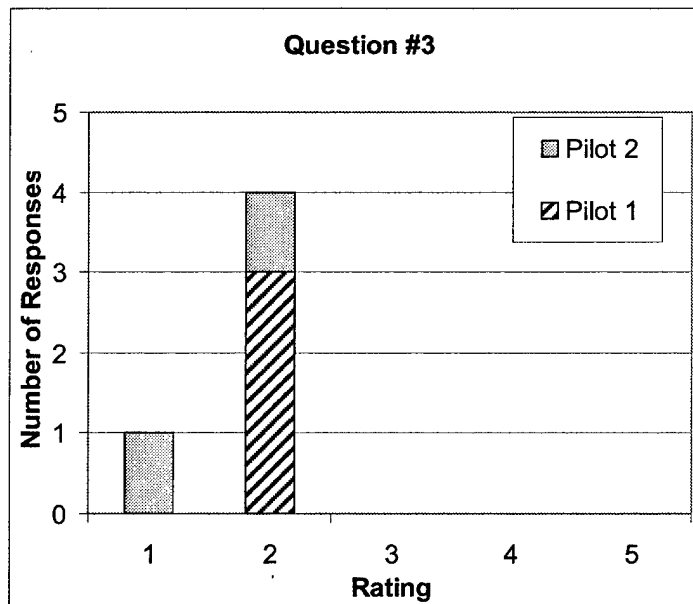
Extremely Predictable – 1    2    3    4    5 – Extremely Unpredictable



Specific Comments: (See Results and Analyses section)

3. Rate and provide comments about aircraft motions while holding the commanded position prior to or in between lead maneuvers

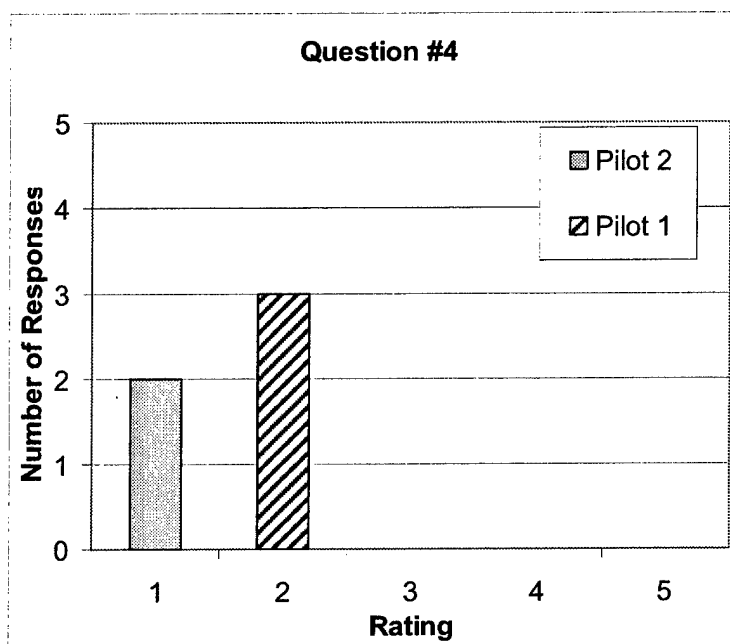
Extremely Smooth – 1    2    3    4    5 – Extremely Objectionable



Specific Comments: (See Results and Analyses section)

4. Rate and provide comments about aircraft motions while holding the commanded position during lead maneuvers.

Extremely Smooth – 1    2    3    4    5 – Extremely Objectionable



Specific Comments: (See Results and Analyses section)

5. Rate and provide comments about the oscillatory response in each control channel as a result of lead maneuvering.

Pitch:      Oscillatory? Yes/No (**Yes: 0 responses; No: 5 responses**)

Damped Immediately – 1    2    3    4    5 – Oscillations Diverged

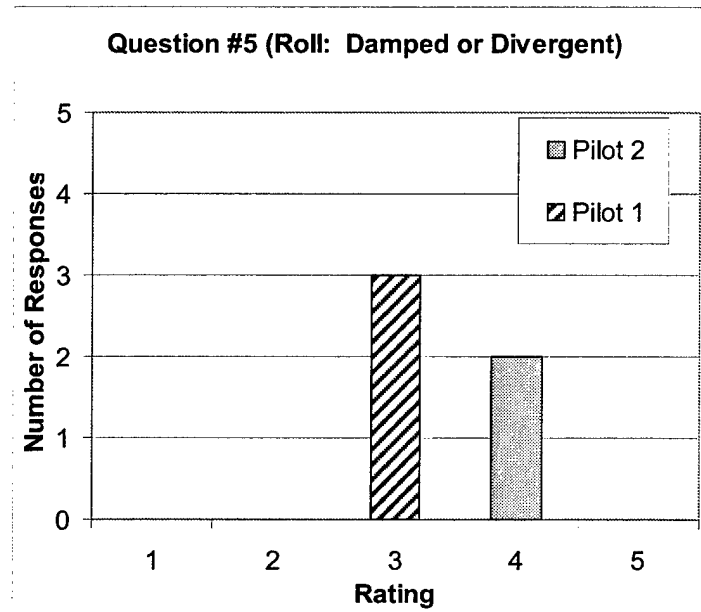
**(Not applicable: no oscillations in pitch)**

Hardly Noticeable – 1    2    3    4    5 – Extremely Objectionable

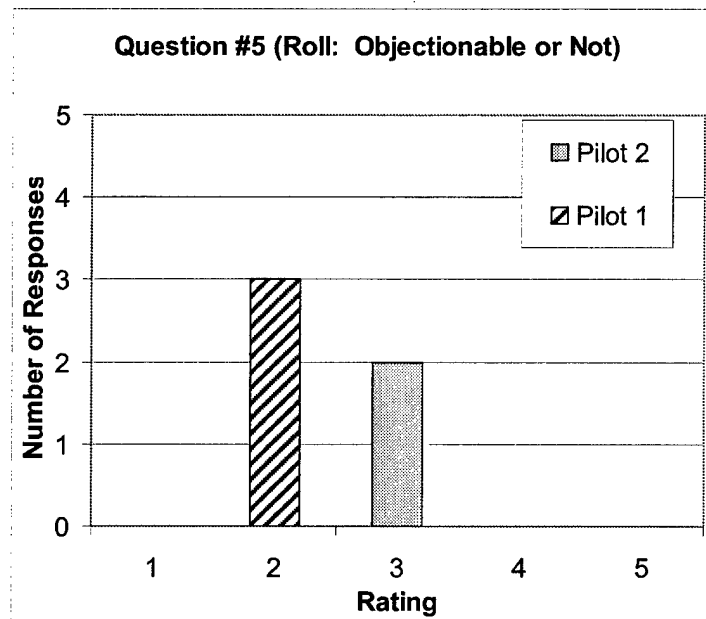
**(Not applicable: no oscillations in pitch)**

Roll: Oscillatory? Yes/No (Yes: 5 responses; No: 0 responses)

Damped Immediately – 1 2 3 4 5 – Oscillations Diverged

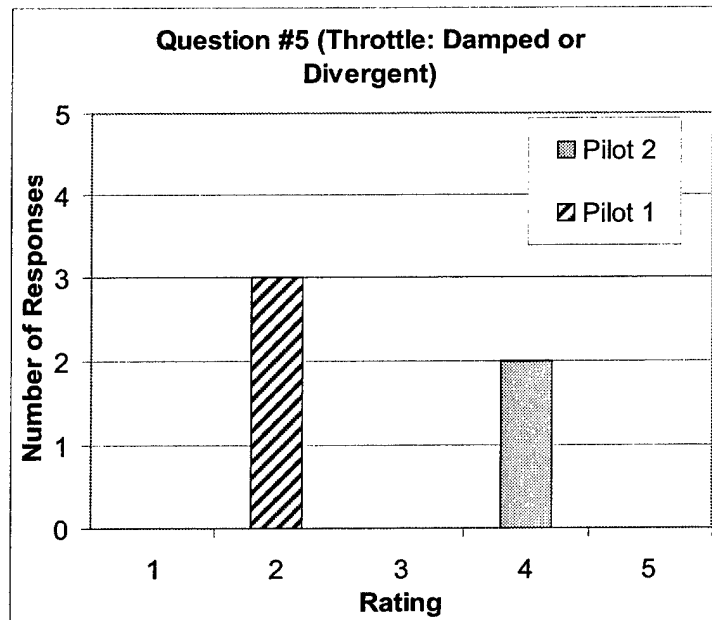


Hardly Noticeable – 1 2 3 4 5 – Extremely Objectionable

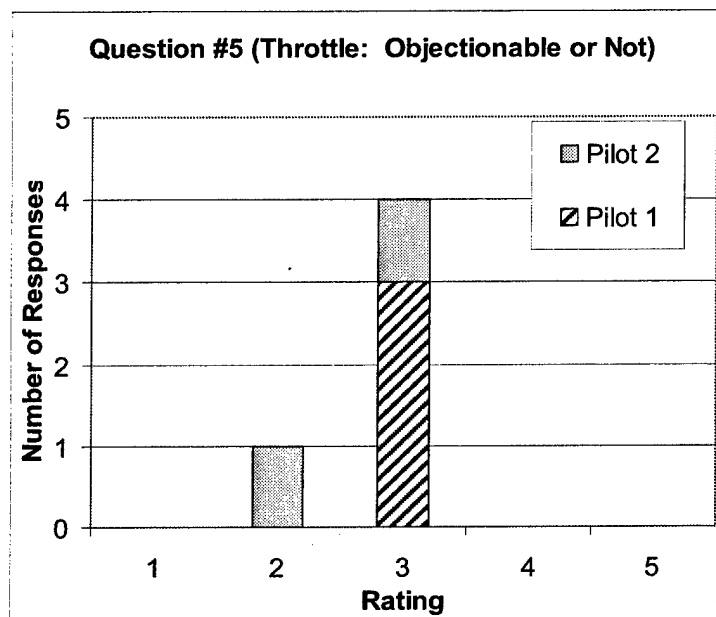


Throttle: Oscillatory? Yes/No (Yes: 5 responses; No: 0 responses)

Damped Immediately – 1    2    3    4    5 – Oscillations Diverged



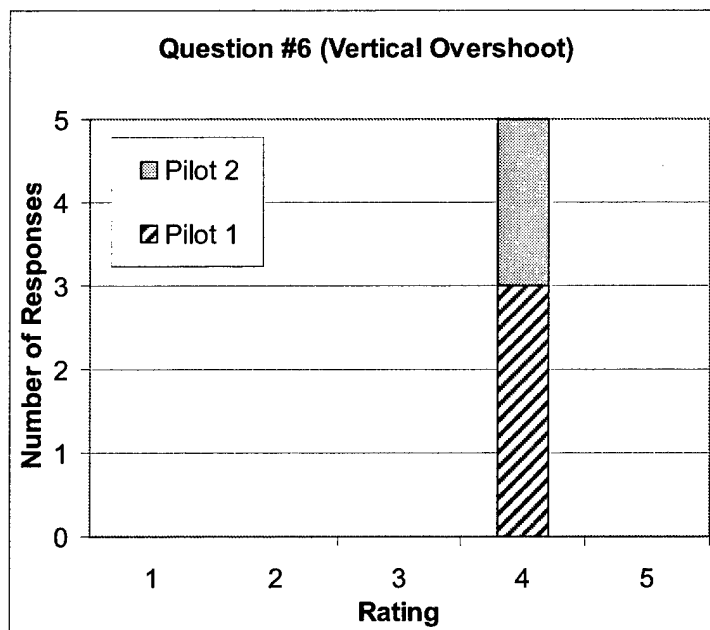
Hardly Noticeable – 1    2    3    4    5 – Extremely Objectionable



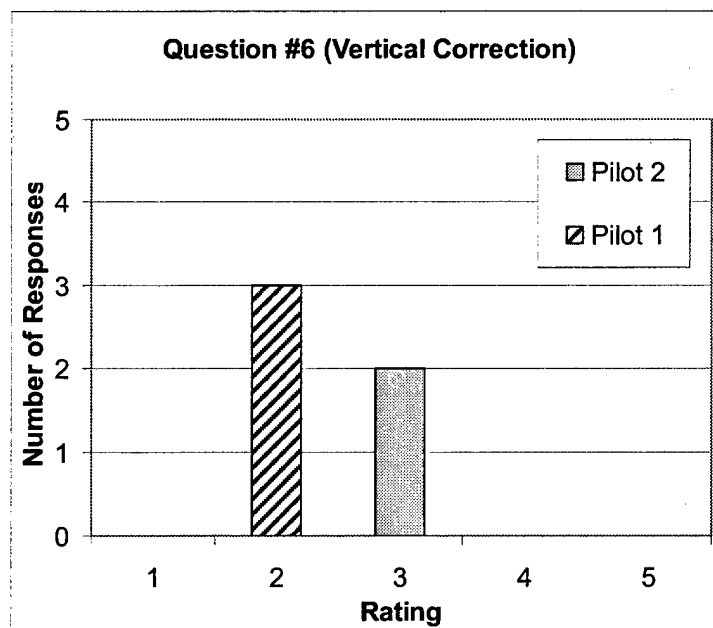
Specific Comments: (See Results and Analyses section)

6. Rate and provide comments about the overshoot tendency of the controller during formation changes when lead was not maneuvering.

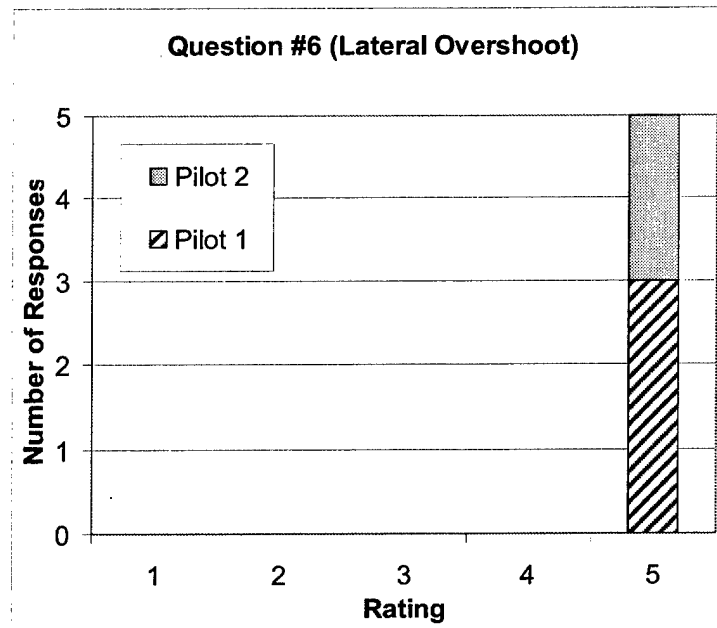
Vertical: No Overshoot – 1 2 3 4 5 – Significant Overshoot(>10ft)



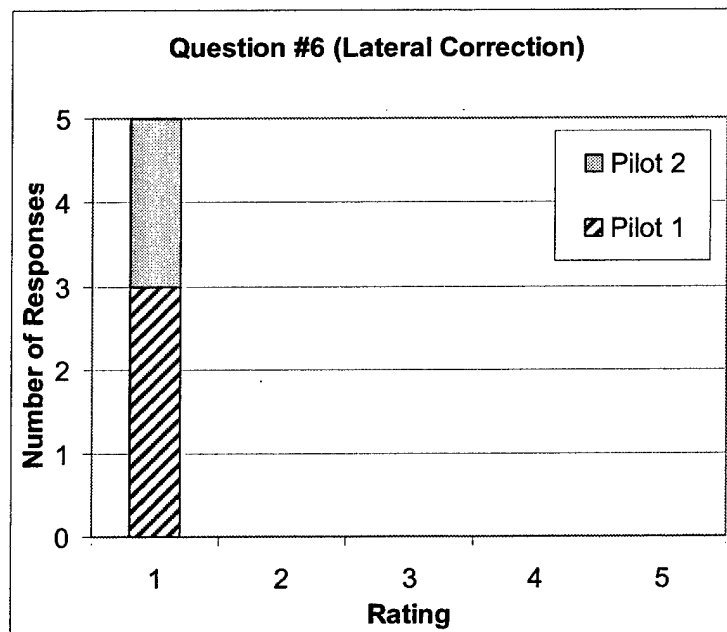
Correction Too Slow – 1 2 3 4 5 – Correction Too Fast



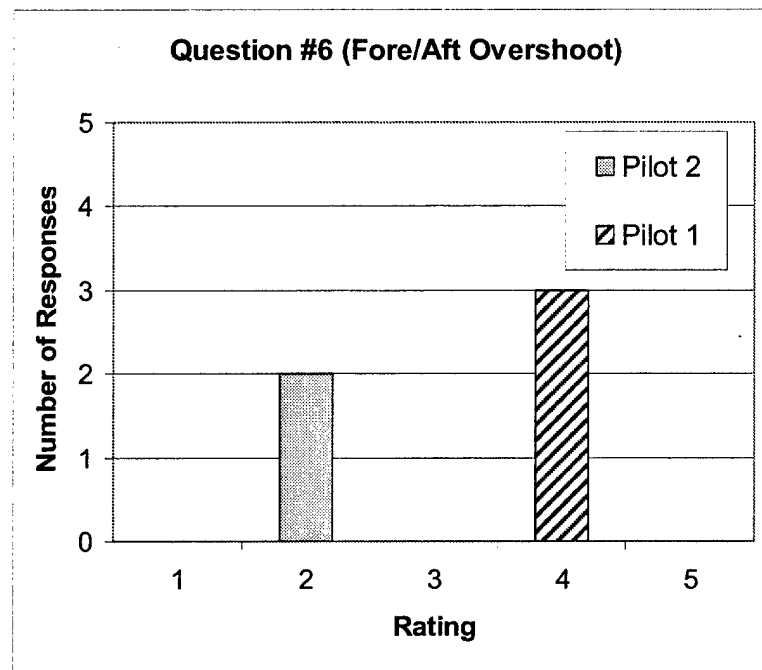
Lateral: No Overshoot – 1 2 3 4 5 – Significant Overshoot(>10ft)



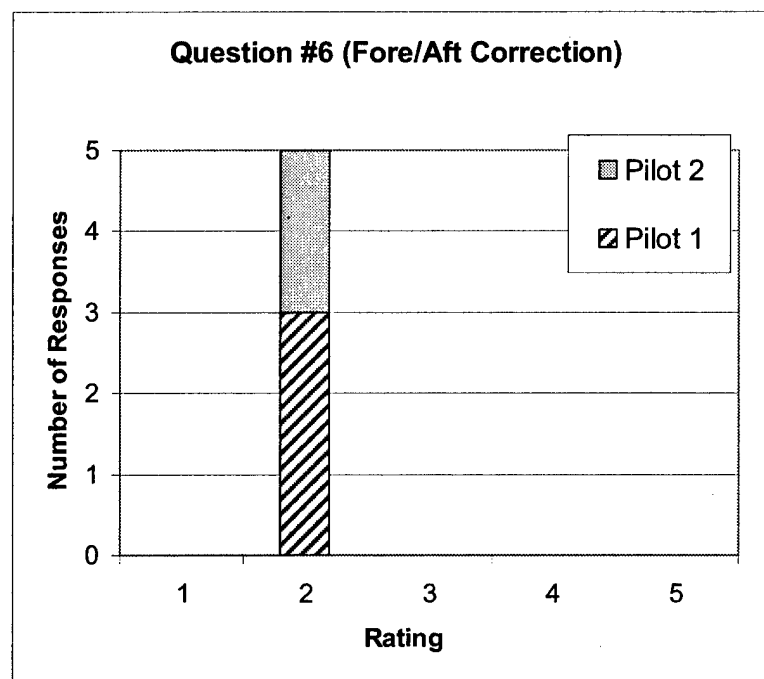
Correction Too Slow – 1 2 3 4 5 – Correction Too Fast



Fore/Aft: No Overshoot – 1 2 3 4 5 – Significant Overshoot(>10ft)



Correction Too Slow – 1 2 3 4 5 – Correction Too Fast



Specific Comments: (See Results and Analyses section)

7. Were any combined (climb and turn, etc...) lead maneuvers conducted?

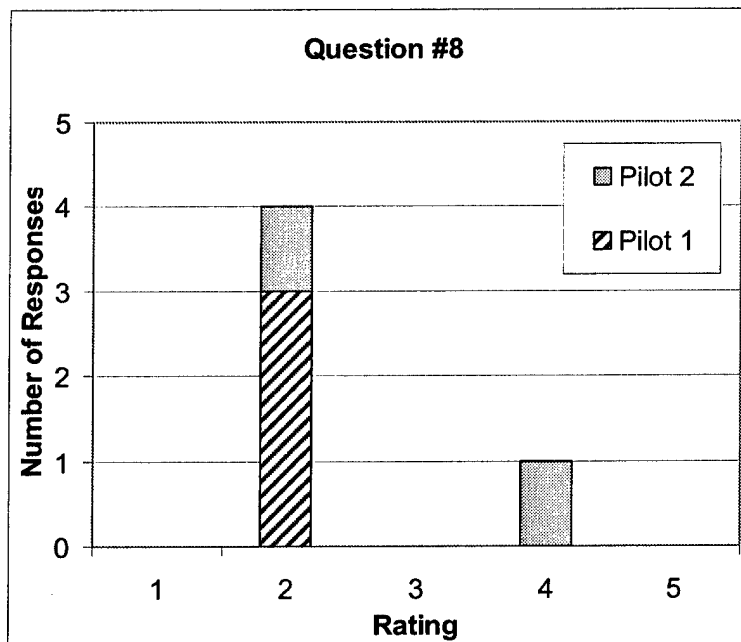
(Yes: 5 responses; No: 0 responses)

If yes, were there any uncomfortable or unexpected motions?

(See Results and Analyses section)

8. Rate and provide comments about the level of difficulty a manned aircraft would encounter flying wingtip formation off of an aircraft being controlled by the AFFC.

Extremely Easy – 1    2    3    4    5 – Extremely Difficult



Specific Comments: (See Results and Analyses section)

9. Was there a noticeable control difference between the vertical, lateral, or fore/aft control channels? (Yes: 5 responses; No: 0 responses)

Which channel appears most stable/most unstable?

Which channel displays the greatest amount of oscillation?

(See Results and Analyses section)

10. How many system kick-offs, when a VISTA safety limit threshold is exceeded and the VSS is disengaged, were experienced? (1 response)

Which channel seemed to give the greatest number of system kick-offs?

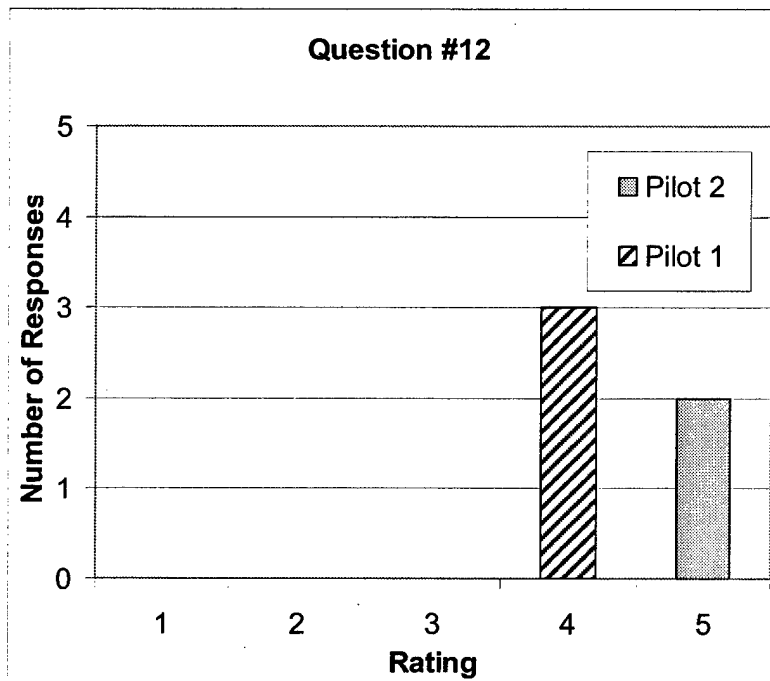
(See Results and Analyses section)

11. Were there any notable issues during the disengagement of the AFFC system?

(1 response; see Results and Analyses section)

12. Rate and provide comments about the throttle control during engaged maneuvering.

Normal Throttle Control – 1    2    3    4    5 – Extremely Erratic Throttle Control



Specific Comments: (See Results and Analyses section)

13. Other Comments: (See Results and Analyses section)

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## **Appendix C – AFFC Algorithm Test Item Description**

## AFFC Algorithm

This section details the control laws and parameters utilized by the AFFC system. The control algorithm that was on the vehicle to perform the formation control is explained below. The Simulink® model that was installed in the VISTA's on-board memory to execute the control system is presented in Figure 5 below.

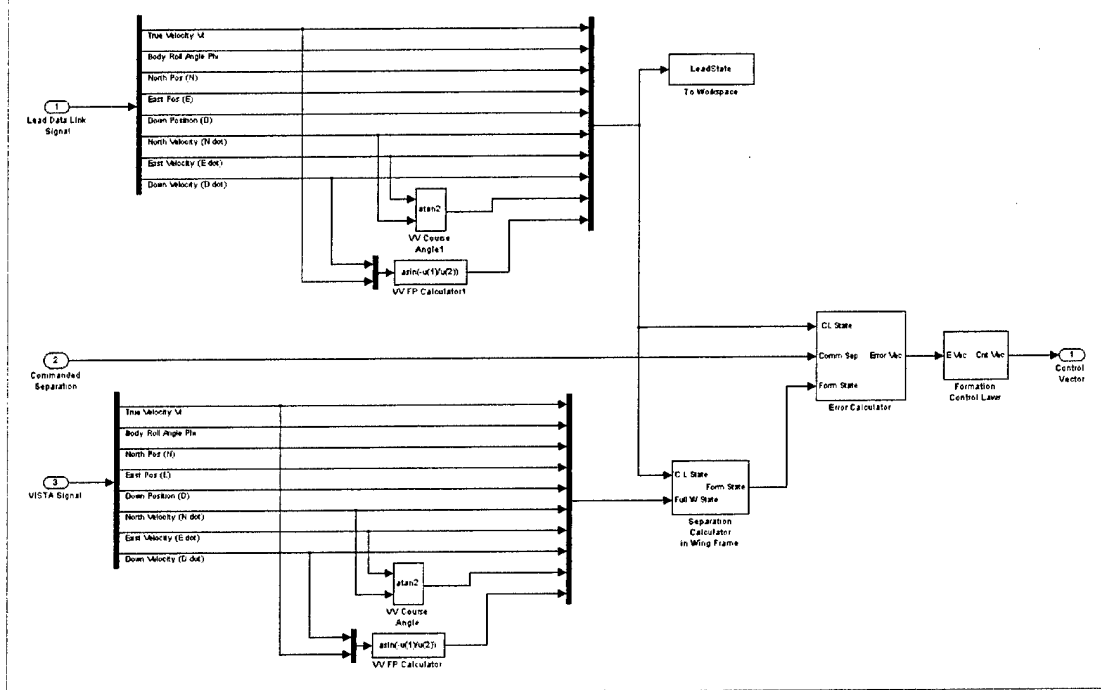


Figure 4 – AFFC Simulink® Model

## Error Signal

The controller was given a position to maintain, or go to, that was represented as a separation in the x, y and z directions expressed in the wing wind axes system. The current separation was calculated from the raw data link information and the VISTA's inertial position. The difference between the commanded and actual separation in each axis represented the errors that must be forced to zero. In addition to the positional errors, the error between the lead and wing flight path angle, roll angle, and velocities were used to control the wing aircraft, and in most cases expected to be driven to zero. The error vector was then calculated as:

$$Errorvec = \begin{bmatrix} x_e \\ y_e \\ z_e \\ V_e \\ \phi_{Ve} \\ \gamma_e \end{bmatrix} = \begin{bmatrix} x_d - x_{Comm} \\ y_d - y_{Comm} \\ z_d - z_{Comm} \\ V_L - V_W \\ \phi_{VL} - \phi_{VW} \\ \gamma_L - \gamma_W \end{bmatrix}$$

where  $x_{Comm}$ ,  $y_{Comm}$ , and  $z_{Comm}$  were the commanded separation distances.

### Control Parameters

Control parameters are the aircraft states that can be affected by either a control surface or a throttle setting. The control laws commanded these parameters to generate the desired aircraft response.

The control vector for the VISTA aircraft was:

$$Controlvec_{VISTA} = [Vel, \alpha_V, \phi_V]^T$$

The above control vectors include velocity, angle of attack, and bank angle. Limits were placed on the control parameters to maintain system integrity, and force the wing aircraft to maneuver in a conservative fashion appropriate for close formation flight.

### Control Laws

This section details how the error vector presented above was converted into an actual command input to the aircraft. The basic form of the control laws included proportional and integral control. From above, the six error states we intended to control included:

$$Errorvec = [x_e, y_e, z_e, V_e, \phi_e, \gamma_e]^T$$

These were controlled by three delta control parameters which were added to the equilibrium values required for straight and level flight such that:

$$Controlvec_{VISTA} = \begin{bmatrix} Vel_V \\ \alpha_V \\ \phi_V \end{bmatrix} = \begin{bmatrix} Vel_{oV} + \Delta Vel_V \\ \alpha_{oV} + \Delta \alpha_V \\ \phi_{oV} + \Delta \phi_V \end{bmatrix}$$

The first control law for delta velocity started with lead's velocity and added proportional and integral control on the x error separation and velocity error. The velocity law was:

$$\Delta Vel_V = (Vel_L - Vel_{oL}) + K_{XP}x_e + K_{XI} \int x_e + K_{VP}V_e + K_{VI} \int V_e$$

The angle of attack control law included proportional and integral control on z separation error and flight path error and was found by the equation:

$$\Delta\alpha_V = K_{zP}z_e + K_{zI} \int z_e + K_{\gamma P}\gamma_e + K_{\gamma I} \int \gamma_e$$

Similar to the velocity control law, the control law for bank angle started with lead's bank angle and added proportional and integral control on the y error separation and bank angle error.

$$\Delta\phi_V = (\phi_L - \phi_{oL}) + K_{YP}y_e + K_{YI} \int y_e + K_{\phi P}\phi_{Ve} + K_{\phi I} \int \phi_{Ve}$$

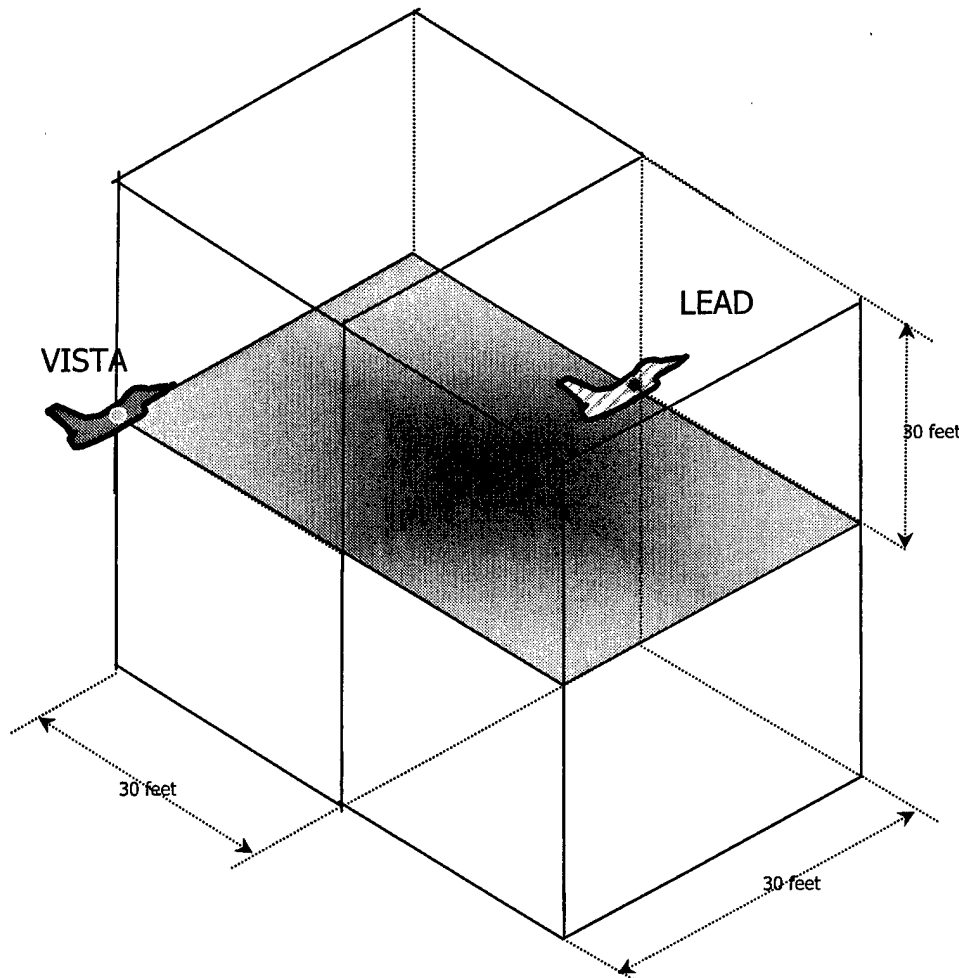
It can be seen from the above three control laws that there is a balance that occurs between the two different error values represented in each law. It was necessary to find the correct gains to balance the two errors in a way that would cause the aircraft to perform adequately. For example, the angle of attack law would continuously try to drive the flight path angles to the same value, but a separation error that was big enough in the z direction would take precedence over the angle error and both would be corrected until a steady state error of zero was reached.

## **Appendix D – Test Maneuver Matrix**

## Test Maneuver Matrix

### Standard position

The relative position in which the VISTA flew, 30 ft aft and 30 ft left with respect to the leader, was defined “standard position”. Most of the maneuvers will be initiated and terminated in this position.



**Figure 5 – Standard Position**

## Test Matrix Description

The test matrix in Table 4 lists position-keeping errors for all the basic maneuvers flown. For each maneuver has been reported:

- Identification number
- Maneuver type
- X error
  1. Time at which the maximum X error occurred
  2. Maximum error value
  3. Comment regarding the X error response
- Y error
  1. Time at which the maximum Y error occurred
  2. Maximum error value
  3. Comment regarding the Y error response
- Z error
  1. Time at which the maximum Z error occurred
  2. Maximum error value
  3. Comment regarding the Z error response

**Table 4-- Summary of position-keeping errors for basic maneuvers**

Maneuver ID	Maneuver Type	Record ID	X error			Y error			Z error		
			Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment
3A	Climb	Sortie 1 Record 4	99.0	11.0	oscillatory, 4 peaks, equally separated, never completely stable kept oscillating btw -2 and Max X error	105.3	19.4	Similar to X error, but with higher period, keeps oscillant about an offset value of about +10 ft 2 large OS	110.375	15.01464	Fairly centered about 0 error just one OS (Max Z error) during leveling after the climb
3A	Climb	Sortie 2 Record 29	98.0	432.0	Large error, constantly increasing	65.3	15.1	1 small negative OS when lead starts climbing... tendency to decrease during maneuver	76.25	7.659908	Fairly centered about 0 error just one OS during leveling after the climb
3A	Climb	Sortie 3 Record 4	77.1	107.0	oscillatory, period about 25 s about two cycle in the time slice of interest, with 2 OS	50.0	11.0	Oscillatory, with period of about 25 s	47.375	18.615712	Fairly centered about 0, Max OS when Lead starts climbing No periodic oscillations were evident
3A	Climb	Sortie 5 Record 1	28.6	12.2	Periodic (T = 10 s) oscillating about offset value, about 8 ft, very slightly decreasing trend There is a high freq oscillation as well, about 1 hz	5.0	23.9	Very long oscillation (T = 27 s) 2 OS during the maneuver	20.421875	14.068596	Fairly Centered about zero Max OS when lead levels off 2 OS
3A	Climb	Sortie 5 Record 3	24.9	77.1	Large spikes in the X error caused by the drop out problems (5 - 6 Spikes in the interval of interest) Major problems at the begin and end of maneuver	12.5	4.4	Very small error no oscillatory trend is evident max error during the steady climb	1.09375	13.122551	Random oscillations about 0 max during steady climb
3A	Climb	Sortie 5 Record 5	1.5	11.1	high freq oscillation No evident low freq period	0.0	5.9	The maneuver was started with a large Y error The controlled well managed the initial error, reducing it to 0 just before the maneuver ends 1 OS was present	14.3125	14.801017	As usual Max errors at beginning and end of Maneuver Tendency to quickly reduced the error to 0 after level off
3B	Descend	Sortie 3 Record 4	132.6	166.2	No noticeable oscillatory mode error increased form zero to an error of about 100 ft there is a large pick of error due to drop out	132.6	56.9	Y error was very close to zero the all time only a spike due to drop out caused the reported max error	126.97	9.80	slightly oscillatory but very close to zero the all time converget characterized by two main modes with period of 15 s and 2 s
3B	Descend	Sortie 1 Record 5	6.6	12.0	Very small error (within 12 ft) centered about zero oscillatory, with 2 major modes low frequency mode, characterized by a period of 10 s high frequency mode, characterized by a period of about 1.2s	15.9	18.5	Moderate error, with one periodic mode characterized by a long period of about 20 s The error is not centered about zero, but exhibits an offset at about 12-15 ft	23.55	10.50	Small error, centered about zero oscillatory, with two major modes: low frequency (T = 10 s) and high frequency (T = 2 s)
3B	Descend	Sortie 5 Record 2	46.9	7.1	Two major oscillatory modes, the low freq one had a period of about 10 s, the high freq mode showed a period of about 1.2 s However, error was very small and very well centered about zero	13.9	9.9	The Y error had a "smooth" trend, one one oscillatory mode was present This mode is rapidly convergent and exhibits a period of about 27 s	14.88	7.76	very oscillatory, but with very small error and centered about zero Beside a high freq mode, the trend is randmic

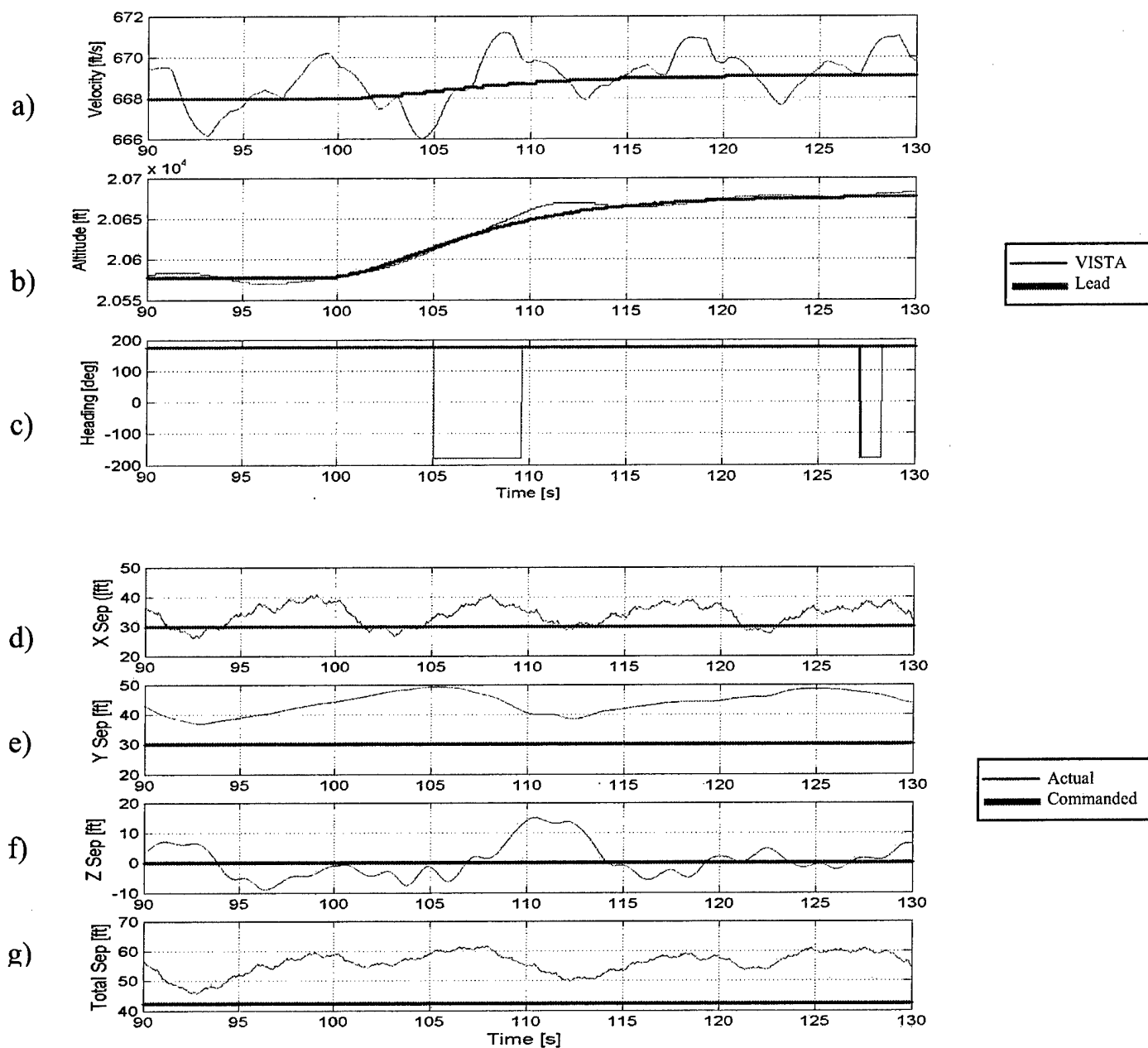
Maneuver ID	Maneuver Type	X error			Y error			Z error		
		Record ID	Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment	Time [s]	Max [ft]
4A	Accel	Sortie 1 Record 1	27.67	69.09	Most noticeable frequency in response was 0.7 Hz. Ramp at t=25 due to data dropout. Max error (other than dropout) was approx 16 ft. Steady state value included approx 5 ft error.	12.06	17.46	Low frequency, 0.05 Hz. Amplitude 8 ft. Slowly convergent with a steady state error of 10 ft.	19.39	12.54
4A	Accel	Sortie 5 Record 1	61.39	8.148	Two frequencies in response, 0.7 Hz and 4 Hz. Great deal of high frequency noise. Steady state value included approx 5 ft error.	34.36	2.69	Low frequency, 0.06 Hz. Amplitude 3 ft. Slowly convergent with a steady state error of 2 ft.	45.50	16.11
5A	Lead turn left 10 deg	Sortie 1 Record 8	74.9	33.5	Error correcting initially (Good Heading) After 10 deg heading change, x drifts aft. Worse case error at run finish	34.0	31.4	Initial Error of 15 feet, increasing trend. Corrects initial error, but grows to worse case. Settles to small oscillation around zero.	54.344	20.66
5A	Lead turn left 10 deg	Sortie 4 Record 1	79.6	67.4	Error spikes at 10 seconds, data drop out. Generally drifts forward until maneuver completion	77.8	38.6	Starts at 0 error. Oscillates around 10 foot steady state error. Turn near end causes another large oscillation.	64.969	25.879
5A-5F	Lead turn left and right 10/20/30 deg	Sortie 3 Record 12	258.1	106.8	Corrects back to zero until heading checks of 20 degrees. 3 data drop outs. Max error at end after 30 degree turn	262.0	80.9	Disturbances due to turns are corrected back to zero. Slow oscillation. Max error at end after 30 degree turn	269.28	56.457
5B	Lead turn Left 20 deg	Sortie 1 Record 10	41.8	76.7	20 feet of initial error, stable rate slow correction to zero following turn, error grows constant, max at end maneuver	33.0	24.7	0 error initially, stable rate error grows to 30 feet during turn after rollout error traded with y channel, corrects to zero	23.469	32.928
5D, 5B, 5F	Lead turn right 10 deg left 20 deg right 30 deg	Sortie 4 Record 3	162.6	246.2	0 initial error, stable rate, grows slowly at first until 10 degree right turn, then decreases until 20 degree left turn increases until 30 degree right turn decreases fastest max error from data dropout spike (2 spikes total)	89.3	57.5	Gentle oscillations, larger with greater turns. Always correcting to steady state offset. Offset changed based on heading	111.05	38.849
5C	Lead turn left 30 deg	Sortie 1 Record 3	200.0	105.3	Really a continuous turn that is cut off at 60 degrees heading change. Initial x error, correcting slowly until turn starts and then drifts forward. Max error at end because of drift	200.0	50.8	Initial error 0 feet, corrects to zero error until turn starts. Increases greatly as x increases in turn. Max error at end	164.69	27.71
5C	Lead turn left 30 deg	Sortie 1 Record 13	36.8	92.0	Initial error spike 5 seconds after start, data drop out, this was max error. Corrects to approx 10 feet error until maneuver at 84 seconds. After turn, drifts forward	83.9	132.5	Initial error 110 feet, doesn't correct until 84 sec at maneuver start. Corrects back, but result cut off. Max error at point of maneuver start	86.766	61.371
5E	Lead turn right 20 deg	Sortie 1 Record 11	28.5	160.8	Initial error 100 feet, increases until 20 degree heading change. Then slowly tapers off and holds near max error	36.0	16.5	Initial error of 10 feet, stable. Corrects until 20 degree turn starts. Corrects again after turn complete. Max error at rollout from turn	17.734	22.888
5F	Lead turn right 30 deg	Sortie 1 Record 14	8.7	37.0	Initial error 30 feet, grows to max until 20 degree turn then passes thru zero and stabilizes on other side at 30 feet. Slowly correcting	48.5	366	Initial error starts near zero, ramps up throughout run. Reason unknown, max value at run completion	29.938	75.165

Maneuver ID	Maneuver Type	Record ID	X error			Y error			Z error		
			Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment
14A	VISTA move 30 ft right from std pos	Sortie 1 Record 16	0.3	28.2	Initial error is max, decreases throughout to approximately 10 feet	0.0	37.4	Initial error is max error position change commanded, overshoots approx 10 feet slow, lightly damped oscillation around 5 foot steady state offset	2.3906	4.9133	Less than 5 feet, always correcting
14B	VISTA move 30 ft left to std pos	Sortie 1 Record 21	37.0	9.6	Initial error 5 feet, unaffected by lateral maneuver	18.8	33.0	Overshoots 25 feet, slow, lightly damped oscillation approx 5 foot steady state offset	39.359	5.9509	Less than 6 feet error, always correcting
14A 14B	VISTA move 30 ft right from std pos and back	Sortie 3 Record 13	71.3	13.2	Initial error 5 feet, unaffected by lateral maneuver	51.5	41.2	Overshoots 20 feet, slow, lightly damped oscillation approx 5 foot steady state offset	108.84	32.135	Less than 6 feet error, always correcting Max error is less than 2 command is near end of maneuver run
14A 14B	VISTA move 30 ft right from std pos and back	Sortie 4 Record 3	245.1	117.5	Initial error 5 feet, unaffected by lateral maneuver Max error is data drop out spike	256.7	37.2	Overshoot 1st time 15 feet, slow, oscillating correction damping ration less than .1 Overshoot 2nd time 32 feet at max error, steady state offset for both cases was approx. 5 feet	188.02	6.5613	Less than 7 feet error, always correcting
18A 18B	VISTA move 60 ft right from std pos and back	Sortie 3 Record 16	102.2	129.3	Initial error 5 feet, unaffected by lateral maneuver Max error is data drop out spike	107.0	75.6	Overshoot 1st time 58 feet, slow, oscillating correction damping ration less than .1 Overshoot 2nd time 45 feet at max error, steady state offset for both cases was approx. 5 feet	79.891	9.491	Less than 10 feet error, always correcting
18A 18B	VISTA move 60 ft right from std pos and back	Sortie 4 Record 15	3.8	12.9	Initial error 10 feet, corrected to 5 feet, unaffected by lateral maneuver	86.5	67.8	Overshoot 1st time 55 feet, slow, oscillating correction damping ration less than .1 Overshoot 2nd time 40 feet at max error, steady state offset for both cases was approx. 5 feet	18.438	6.5613	Less than 7 feet error, always correcting
17A	VISTA descend 30 ft from std pos	Sortie 2 Record 5	5.3	72.8	Various spikes due to drop out anyway slightly increasing during maneuver	26.9	10.9	long period oscillation	8.59375	24.566637	Oscillatory with long period
15B	VISTA Climb 30 ft from std pos	Sortie 2 Record 6	0.0	62.7	slightly oscillatory large error	16.5	5.8	Oscillatory, low frequency mode	1.5625	26.519761	Channel of commanded position change commanded value reached with OS OS peak was about 10 ft above the commanded value and about 8 s after the input. steady value reached after 11 s
15A 15 B	VISTA Climb 30 ft from std pos and back	Sortie 3 Record 13	110.3	13.1	two modes, low and high frequency 4 OS of the long period mode in the interval of interest oscillation about offset value of about - 10	93.2	13.5	only low freq mode 3 OS in the period of interest	108.84	32.13	Beside the two altitude changes of the lead, the Z error is almost 0 after each position change the error got to zero in about 1.5 / 2 OS

Maneuver ID	Maneuver Type	X error			Y error			Z error		
		Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment	Time [s]	Max [ft]	Comment
17 A 17 B	VISTA descend 30 ft to std pos and back	172.7	6.8	Oscillatory, but well centered about 0 two major modes, low and high freq (t = 5 s and 0.7 s) The amplitude of the low freq oscillation is 25 feet The modes involved are the same before during and after the actual position change	180.8	6.4	the channel exhibited an oscillatory trend, but the mode characteristics (period and amplitude) were variable. Error centered about zero	185.83	32.07	Channel of commanded position change 1) 17A Max Overshoot value (10 ft above commanded value) was reached 8 s after the commanded change no other OS but a series of very small undershoots 100% commanded value was reached after 4.5 s The Settling time 90% was 12% 2) 17B the response exhibited was very similar to that one just described, both qualitatively and quantitatively
17B	VISTA Climb 30 ft to std pos	19.8	71.0	Not oscillatory, slightly divergent	3.2	7.6	Small error, exhibited a random trend	1.91	33.29	Channel of commanded position change commanded value reached with on only OS OS peak was about 10 ft above the commanded value and about 8 s after the input. Steady value reached after 11 s
16A	VISTA move Forward 30 ft	3.109	30.46	Pseudo-highly damped response to the step input. Minor oscillations at approx 0.8 Hz. Reached 100% rise time in 7 sec. Held commanded value for 5 sec, then overshot by 10 ft, possibly due to heading interactions.	1.00	48.6	Initial error of 50 ft. Low frequency approx 0.05 Hz. Amplitude 35 f but convergent.	20.59	5.49	No consistent frequency in response. Variations from commanded value did not exceed 5 ft.
16A	VISTA move Forward 30 ft	89.02	31.04	Pseudo-highly damped response to the step input. Minor oscillations at approx 0.8 Hz. Reached 100% rise time in 13 sec. Held commanded value for 4 sec before termination.	84.00	5.83	Initial error of 6 ft. Highly damped, gradual return to the commanded value. 100% rise time was 13 sec. Slight oscillations at 0.14 Hz.	87.09	6.41	Most consistent frequency in response was 0.8 Hz. Slight loss of altitude prior to step input was overcome by slight climb as VISTA accelerated. Steady state error was approx 1 ft.
16B	VISTA move Alt 30 ft	13.19	44.04	No response to step input. Signal characterized by 0.1 Hz and 0.7 Hz responses, along with high frequency noise. Presence of noise and lack of response seemed to indicate dead reckoning.	1.00	18.98	Initial error of 20 ft. Gradual 0.05 Hz oscillation around the commanded value. Amplitude 10 ft but convergent to a steady state error of approx 5 ft.	2.83	4.85	Unpredictable variations, possibly affected by the deceleration and/or wind buffet. Most obvious frequency in response was 0.5 Hz
16B	VISTA move Alt 30 ft	120.4	31.95	Two frequencies in response, 0.1 Hz and 0.7 Hz. Reached 100% rise time in 18 sec with an overshoot of 2 ft.	128.9	4.52	Gradual 0.07 Hz oscillation around the commanded value with less than 5 feet of error throughout the maneuver.	113.59	6.53	Unpredictable variations, possibly affected by the deceleration and/or wind buffet. Most obvious frequency in response was 0.4 Hz
19A	VISTA move Forward 60 ft	12.83	86.64	Slight deceleration prior to position change due to data link dropout or internal VISTA INS errors. Despite initial error, x-channel response was a smooth, gradual accel to the commanded value. Very minimal oscillations at 0.8 Hz. Reached 100% rise time in 16 sec with overshoot of 0 ft.	12.72	16.97	Gradual 0.05 Hz oscillation with amplitude of 8 ft and steady state error of 10 ft.	16.91	7.42	Most consistent frequency in response was 0.4 Hz. Variations from commanded value did not exceed 8 ft.
19B	VISTA move Alt 60 ft	41.28	64.85	Two frequencies in response, 0.1 Hz and 0.7 Hz. Reached 100% rise time in 62 sec with an overshoot of 1 ft.	35.00	14.56	Gradual 0.07 Hz oscillation with amplitude of 3 ft and steady state error of 9 ft.	55.70	6.38	Most consistent frequency in response was 0.6 Hz Variations from commanded value did not exceed 7 ft.

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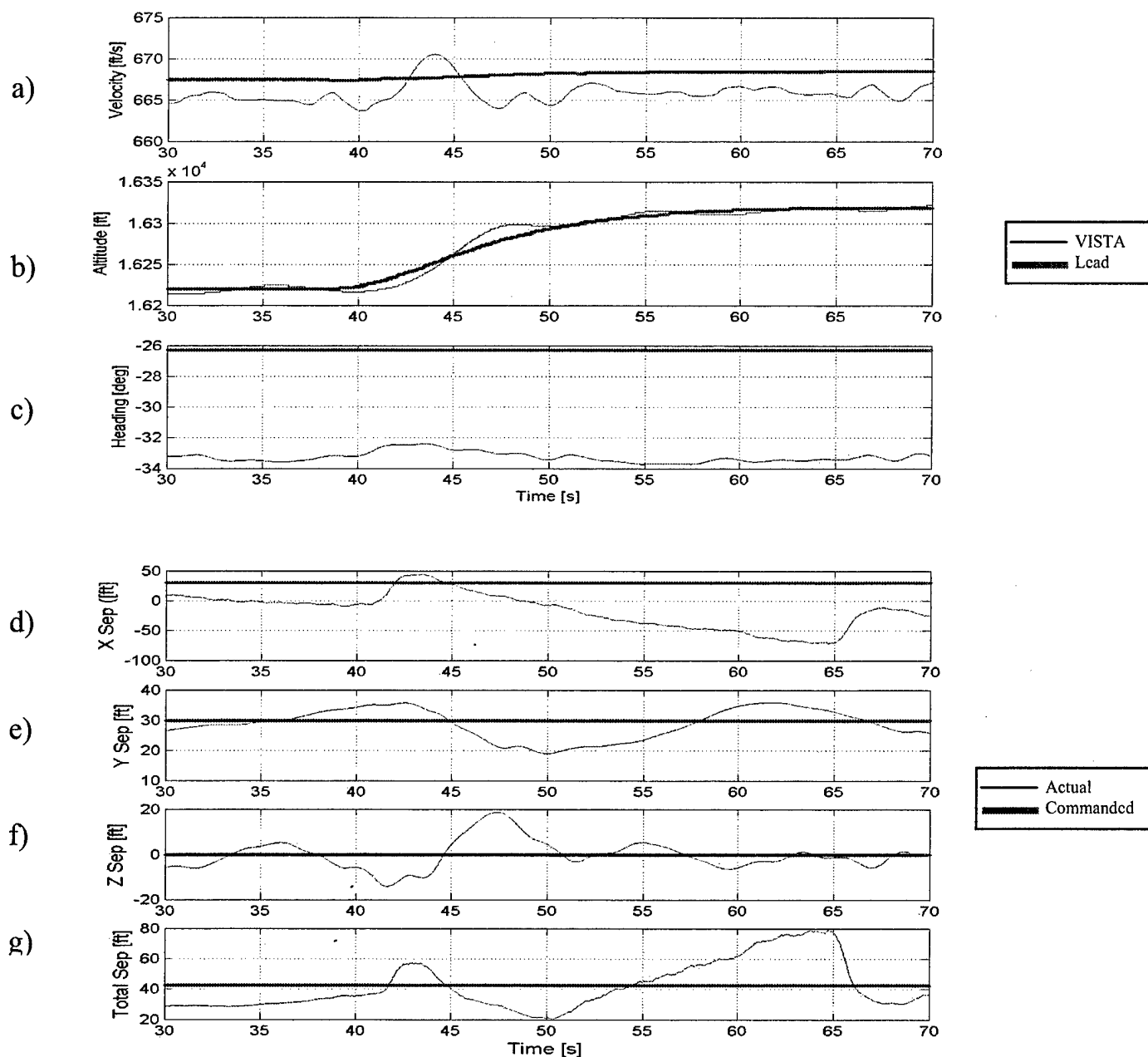
## **Appendix E – Figures**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	11.0	19.4	15.0	19.2
Time of maximum error (seconds)	99.0	105.3	110.4	108.0
Lead Maneuver	Climbs 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

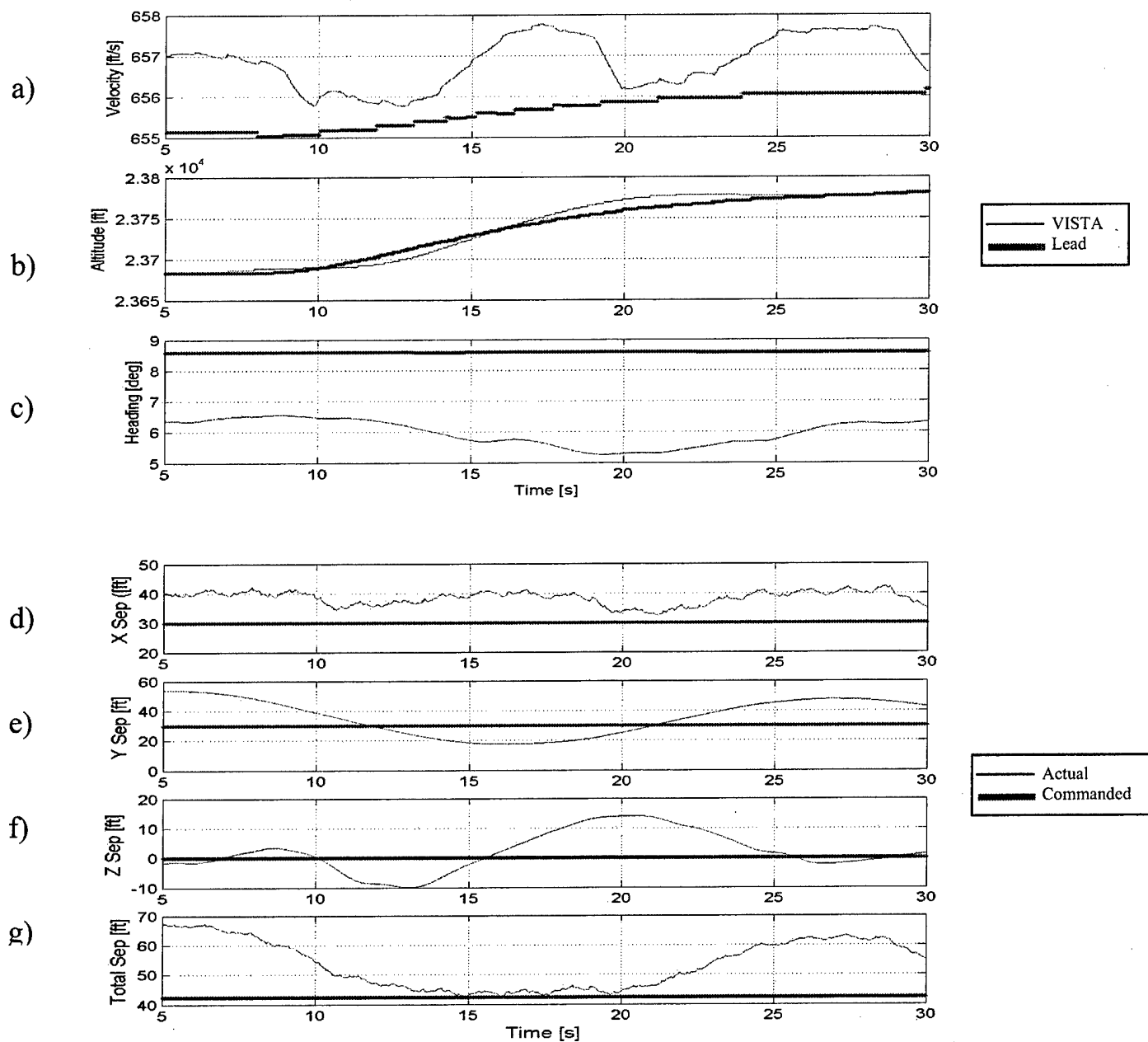
Figure 6 – Event 3A Run 1 (Sortie 1 Record 4)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	107.0	11.0	18.6	38.8
Time of maximum error (seconds)	77.1	50.0	47.4	77.1
Lead Maneuver	Climbs 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

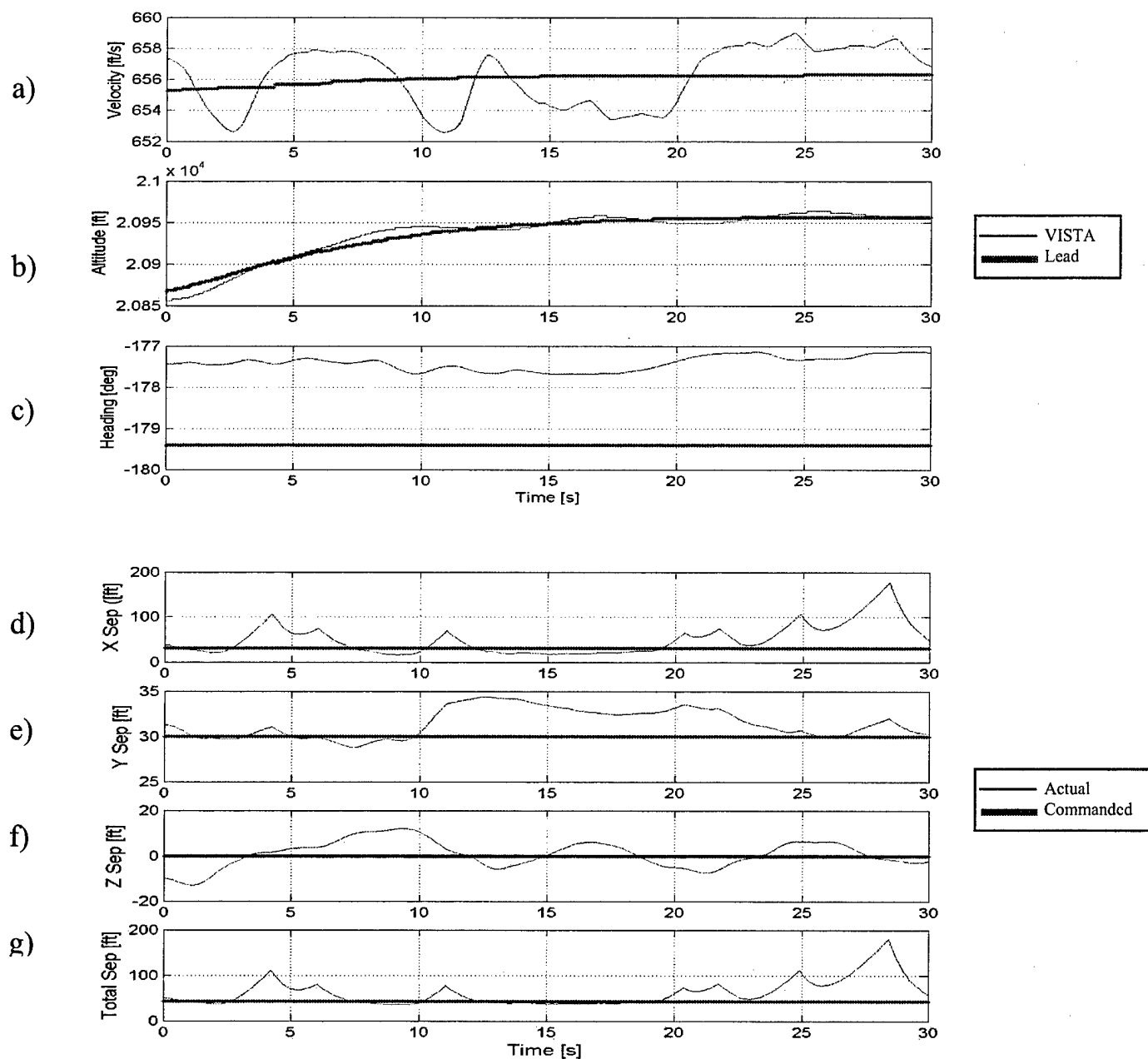
**Figure 7 – Event 3A Run 2 (Sortie 3 Record 4)**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	12.2	23.9	14.1	24.8
Time of maximum error (seconds)	28.6	5.0	20.4	5.1
Lead Maneuver	Climbs 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

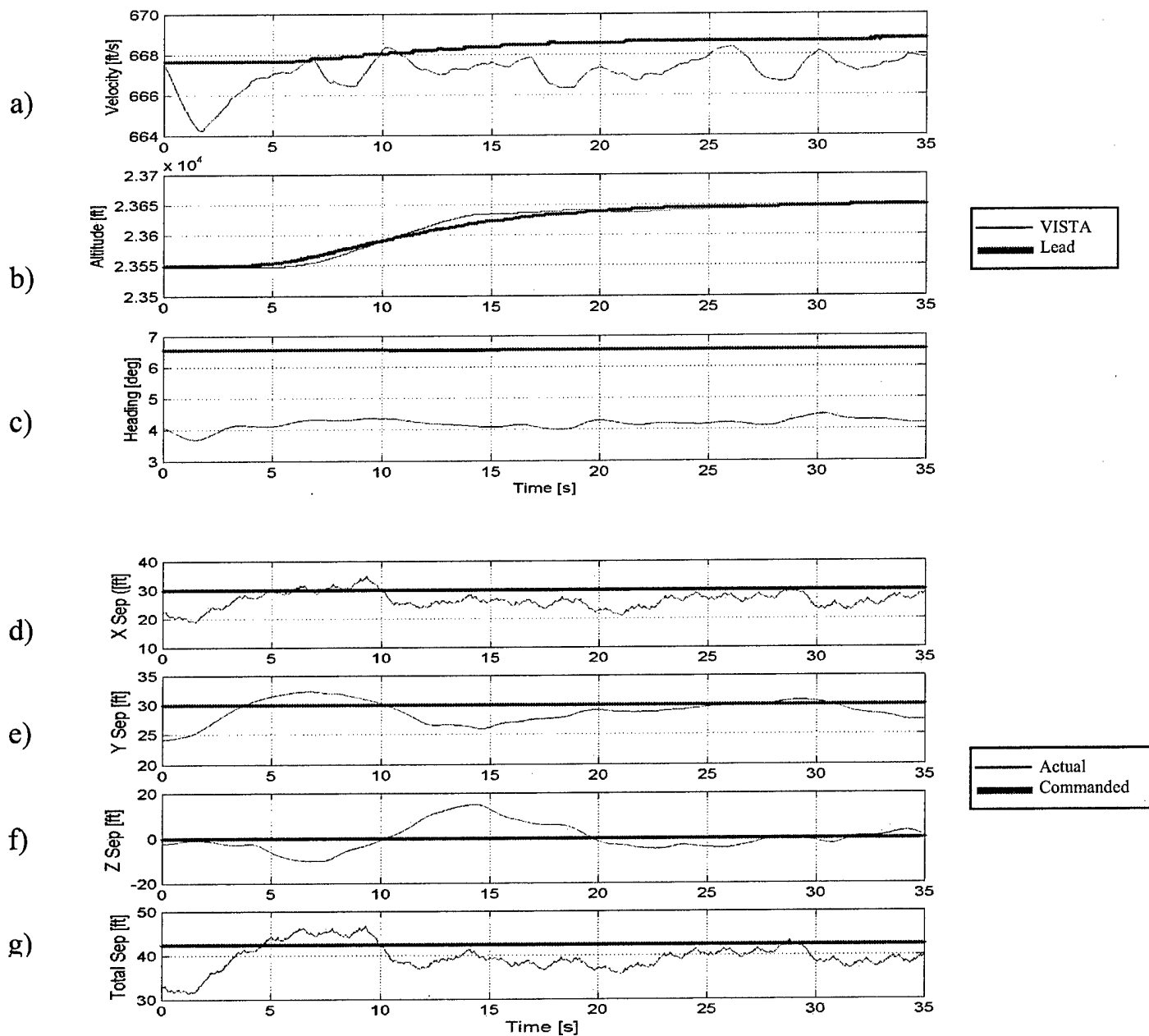
Figure 8 – Event 3A Run 3 (Sortie 5 Record 1)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	77.1	4.4	13.1	69.2
Time of maximum error (seconds)	24.9	12.5	1.1	24.9
Lead Maneuver	Climbs 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

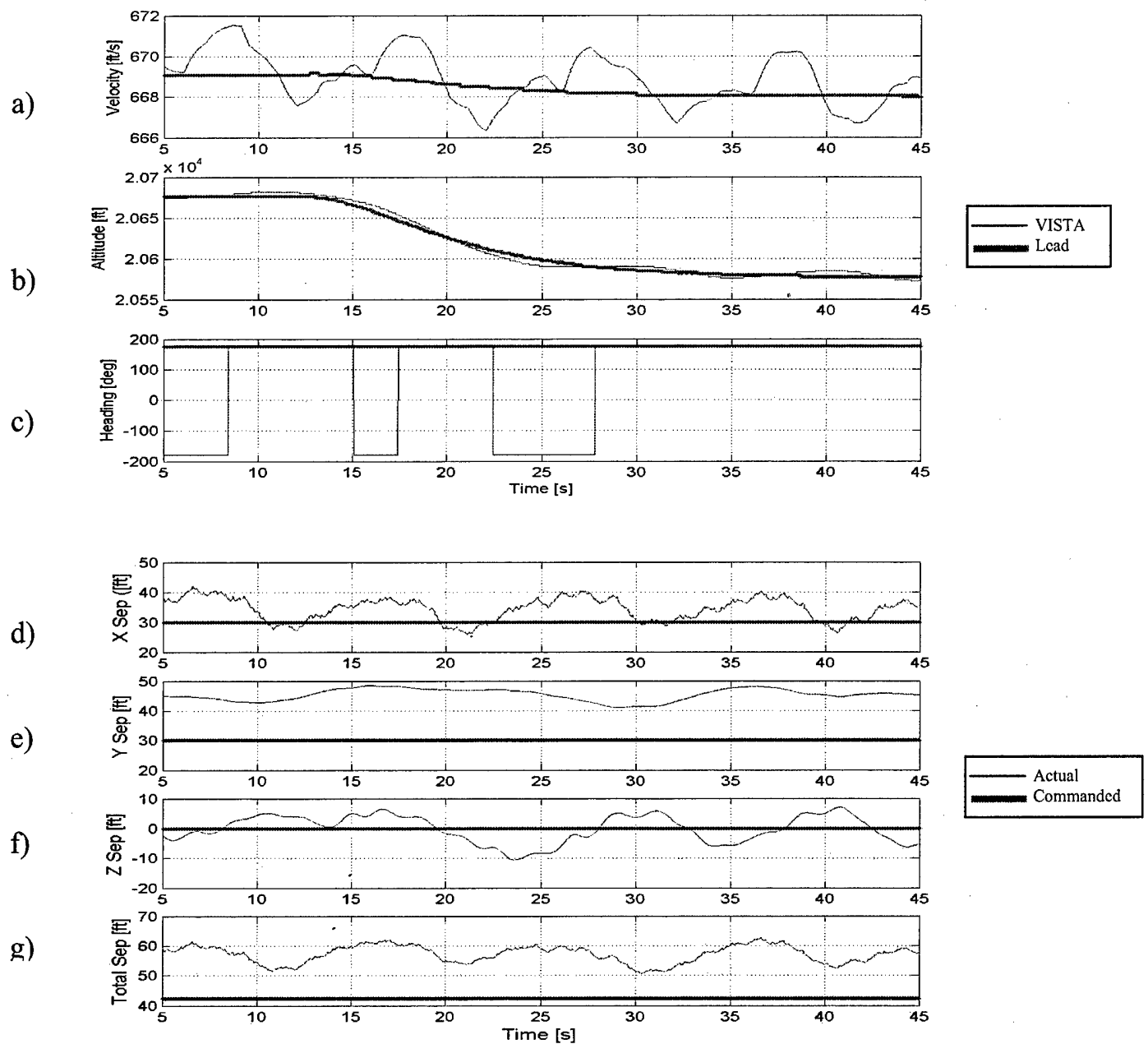
**Figure 9 – Event 3A Run 4 (Sortie 5 Record 3)**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	11.1	5.9	14.8	4.3
Time of maximum error (seconds)	1.5	0	14.3	9.3
Lead Maneuver	Climbs 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

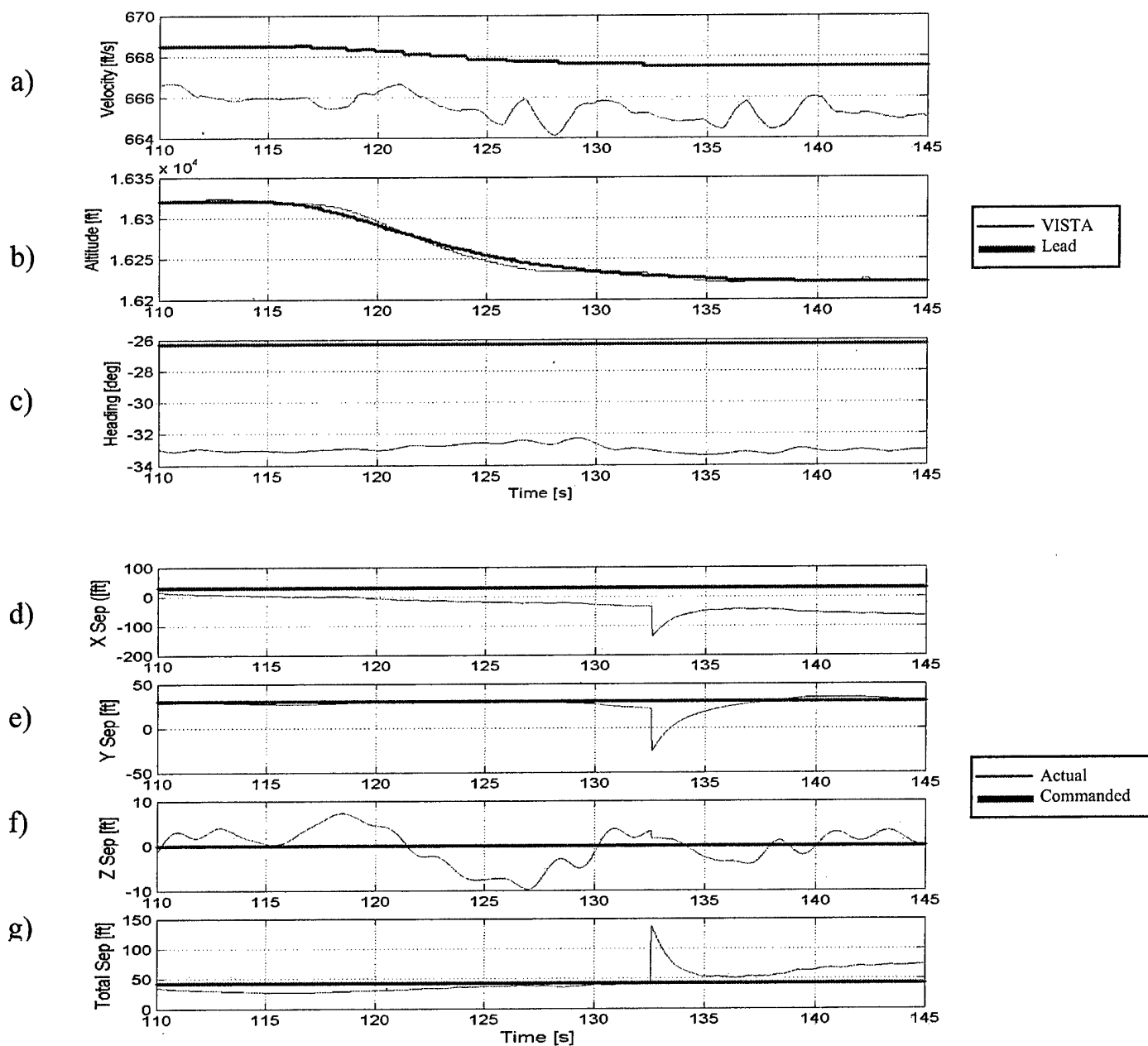
Figure 10 – Event 3A Run 5 (Sortie 5 Record 5)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	12.0	18.5	10.5	20.1
Time of maximum error (seconds)	6.6	15.9	23.5	36.6
Lead Maneuver	Descends 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

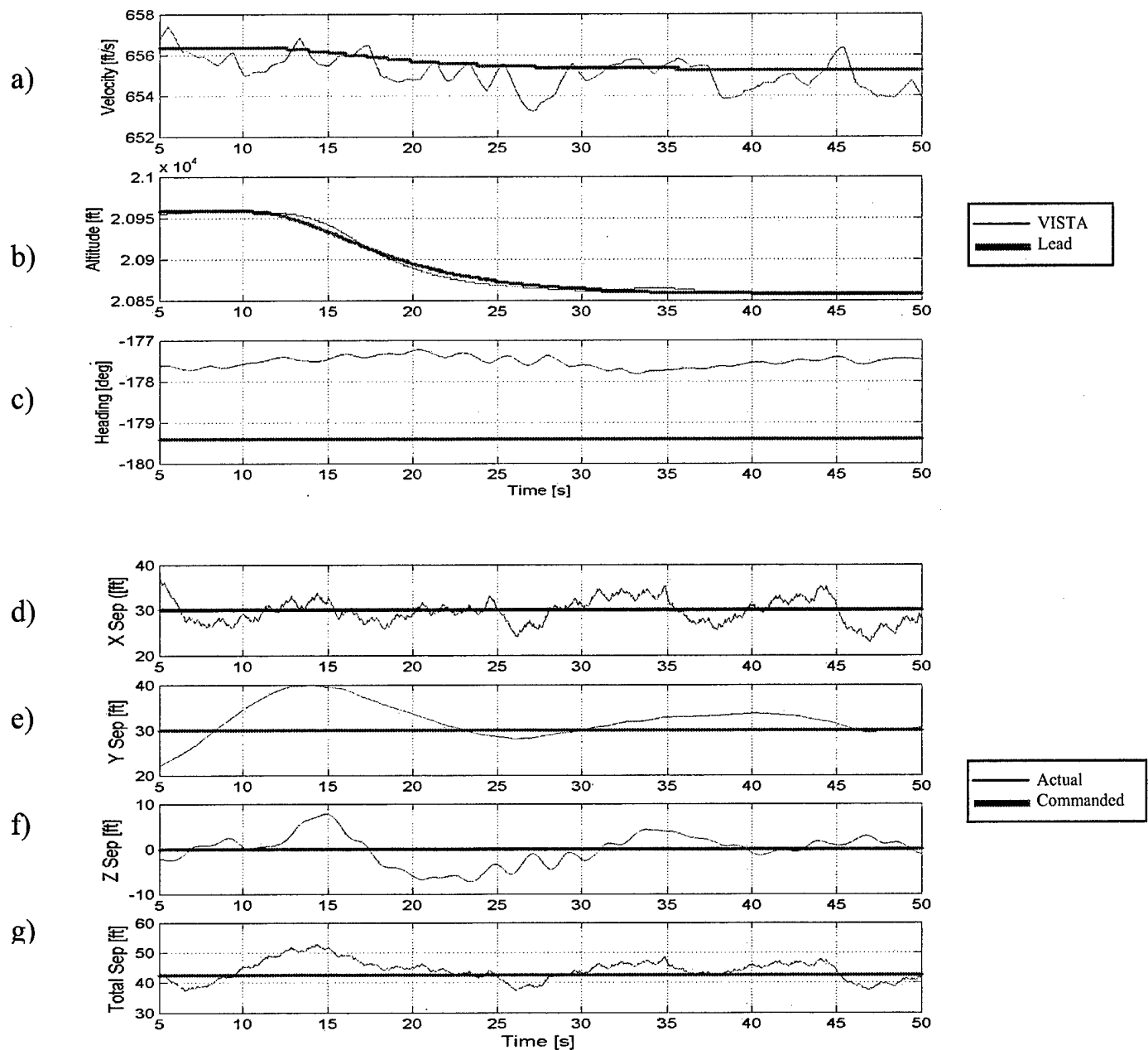
Figure 11 – Event 3B Run 1 (Sortie 1 Record 5)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	166.2	56.9	9.8	96.4
Time of maximum error (seconds)	132.6	132.6	127.0	132.6
Lead Maneuver	Descends 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

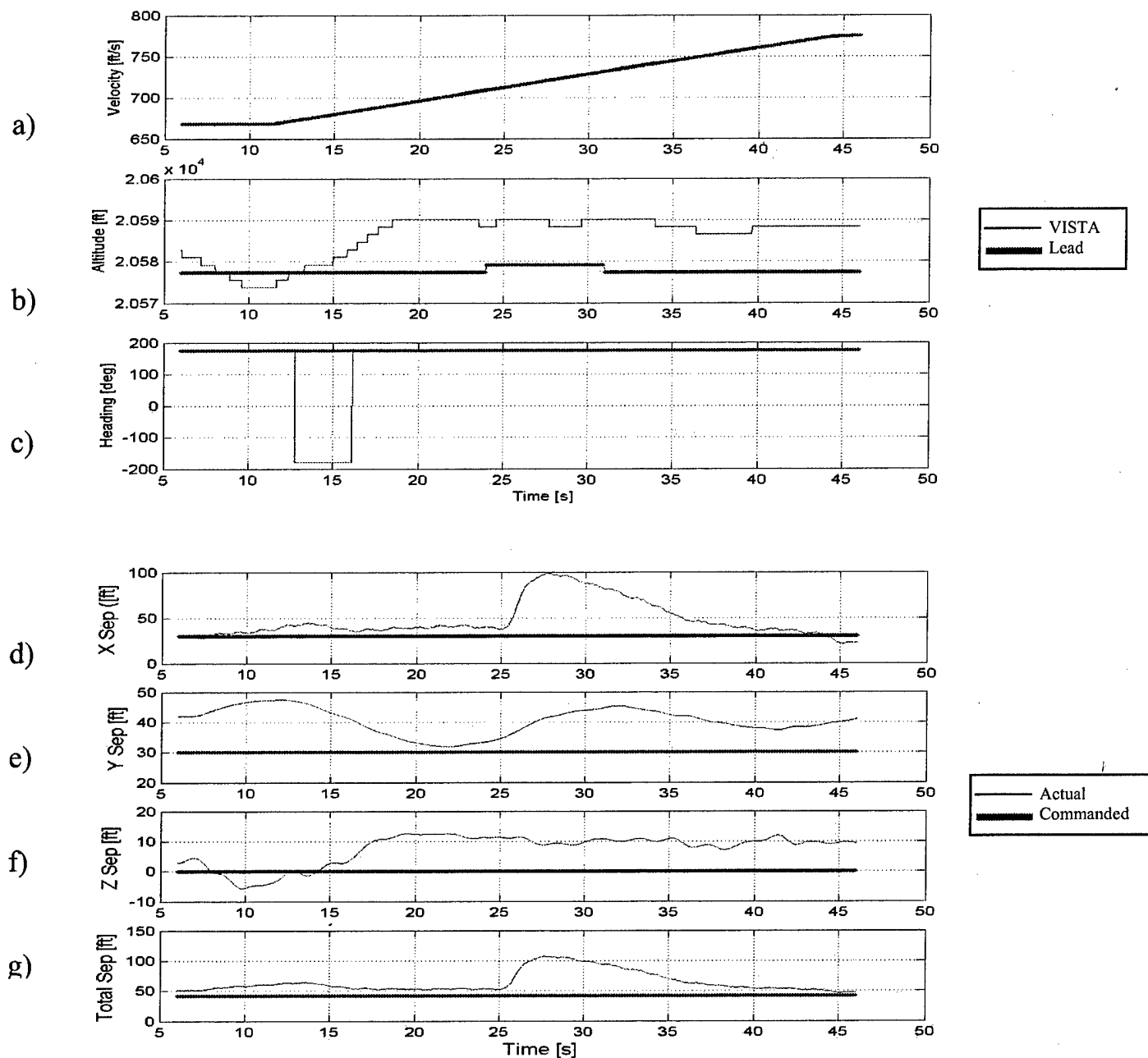
Figure 12 – Event 3B Run 2 (Sortie 3 Record 4)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	7.1	9.9	7.8	10.4
Time of maximum error (seconds)	46.9	13.9	14.9	14.4
Lead Maneuver	Descends 100 feet while VISTA is commanded to maintain standard position (30 30 0)			

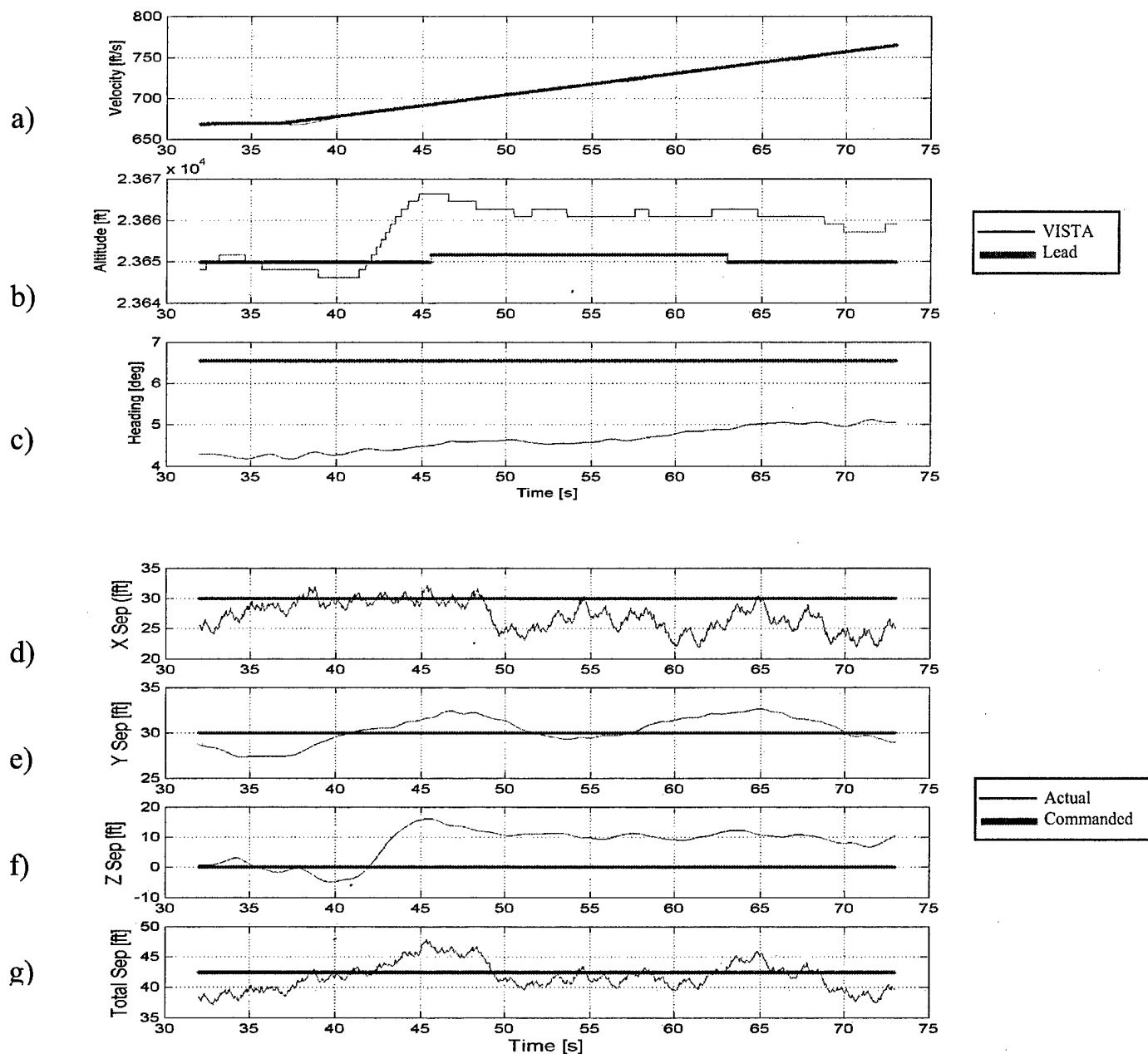
**Figure 13 – Event 3B Run 3 (Sortie 5 Record 2)**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	69.1	17.5	12.5	65.3
Time of maximum error (seconds)	27.7	12.1	19.4	27.7
Lead Maneuver	Accelerates 50 knots while VISTA is commanded to maintain standard position (30 30 0)			

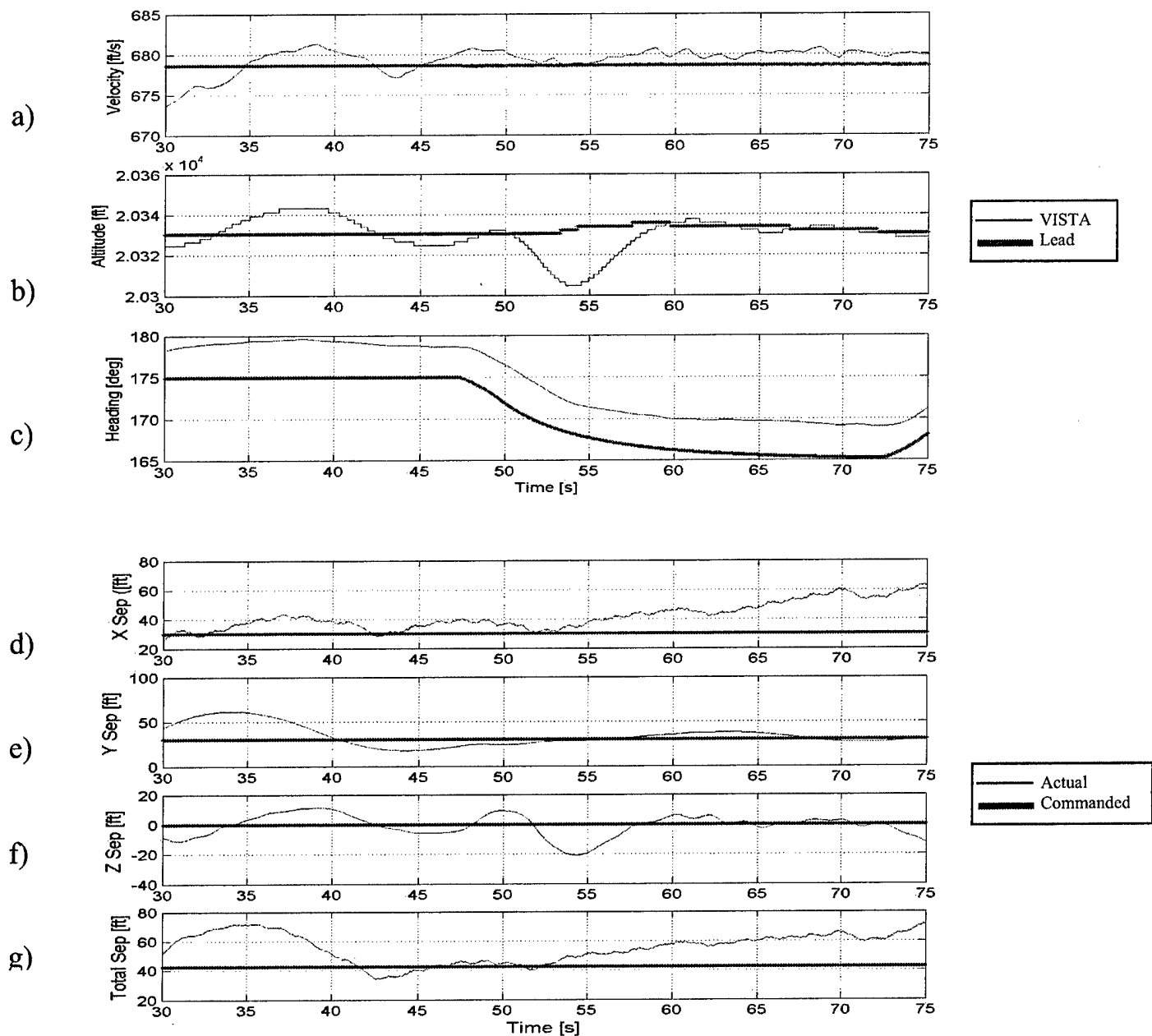
Figure 14 – Event 4A Run 1 (Sortie 1 Record 6)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	8.1	2.7	16.1	5.4
Time of maximum error (seconds)	61.4	34.4	45.5	45.4
Lead Maneuver	Accelerates 50 knots while VISTA is commanded to maintain standard position (30 30 0)			

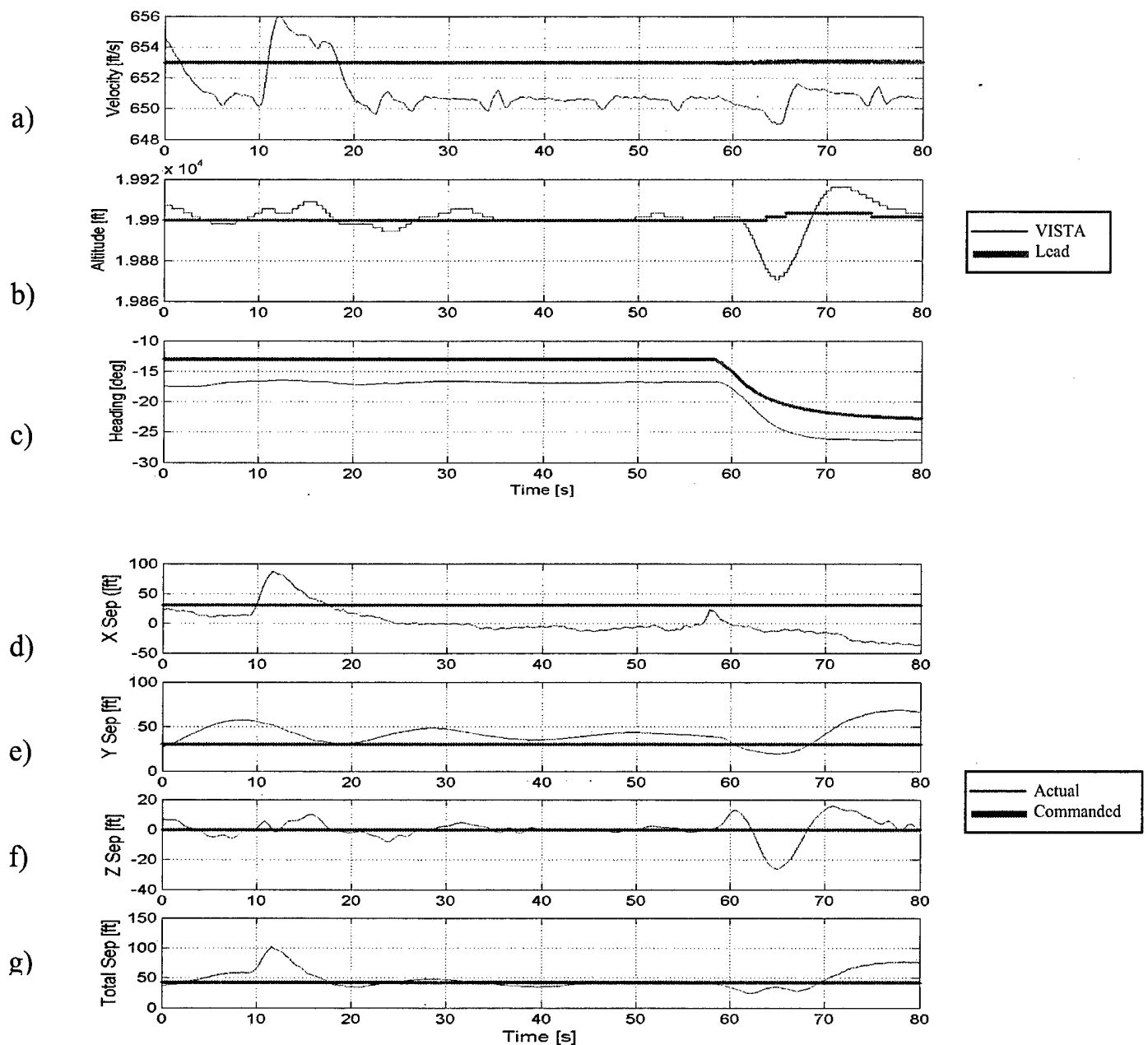
Figure 15 – Event 4A Run 2 (Sortie 5 Record 5)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	33.5	31.4	20.7	29.5
Time of maximum error (seconds)	74.9	34.0	54.3	34.3
Lead Maneuver	Turns left 10 degrees while VISTA is commanded to maintain standard position (30 30 0)			

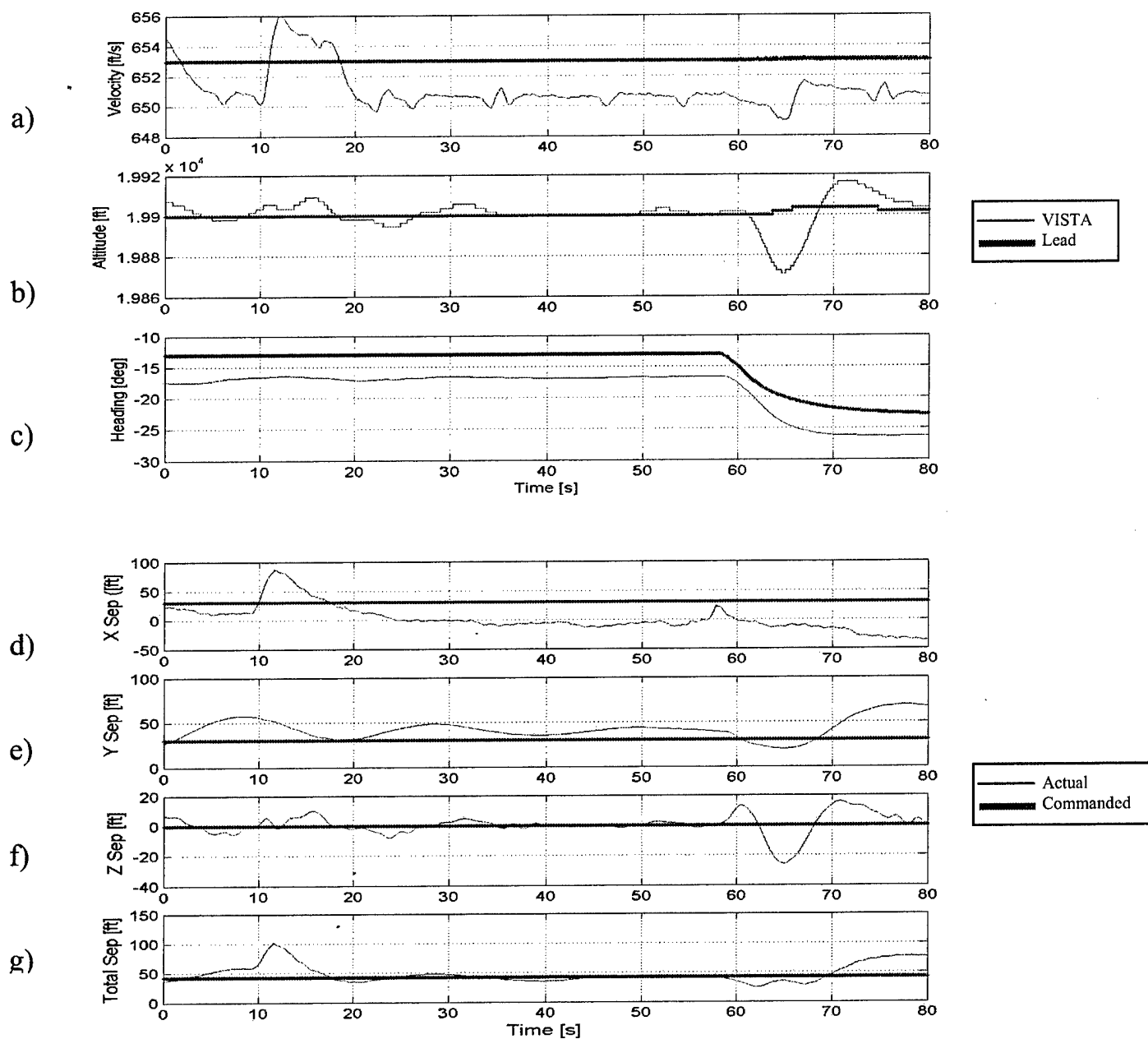
Figure 16 – Event 5A Run 1 (Sortie 1 Record 8)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	67.4	38.6	25.9	59.0
Time of maximum error (seconds)	79.6	77.8	65.0	11.6
Lead Maneuver	Turns left 10 degrees while VISTA is commanded to maintain standard position (30 30 0)			

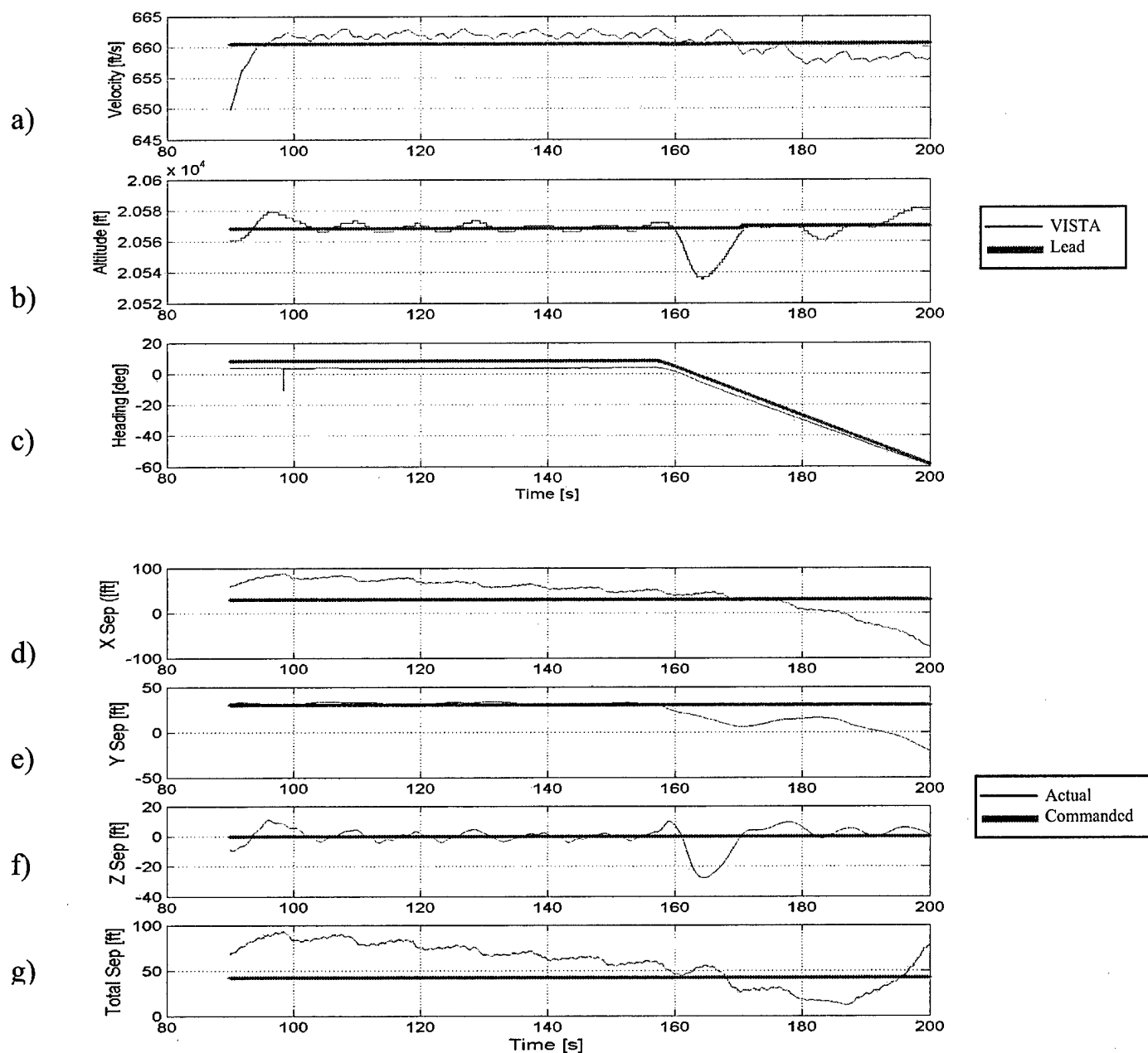
Figure 17 – Event 5A Run 2 (Sortie 4 Record 1)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	76.7	24.7	32.9	66.6
Time of maximum error (seconds)	41.8	33.0	23.5	41.8
Lead Maneuver	Turns left 20 degrees while VISTA is commanded to maintain standard position (30 30 0)			

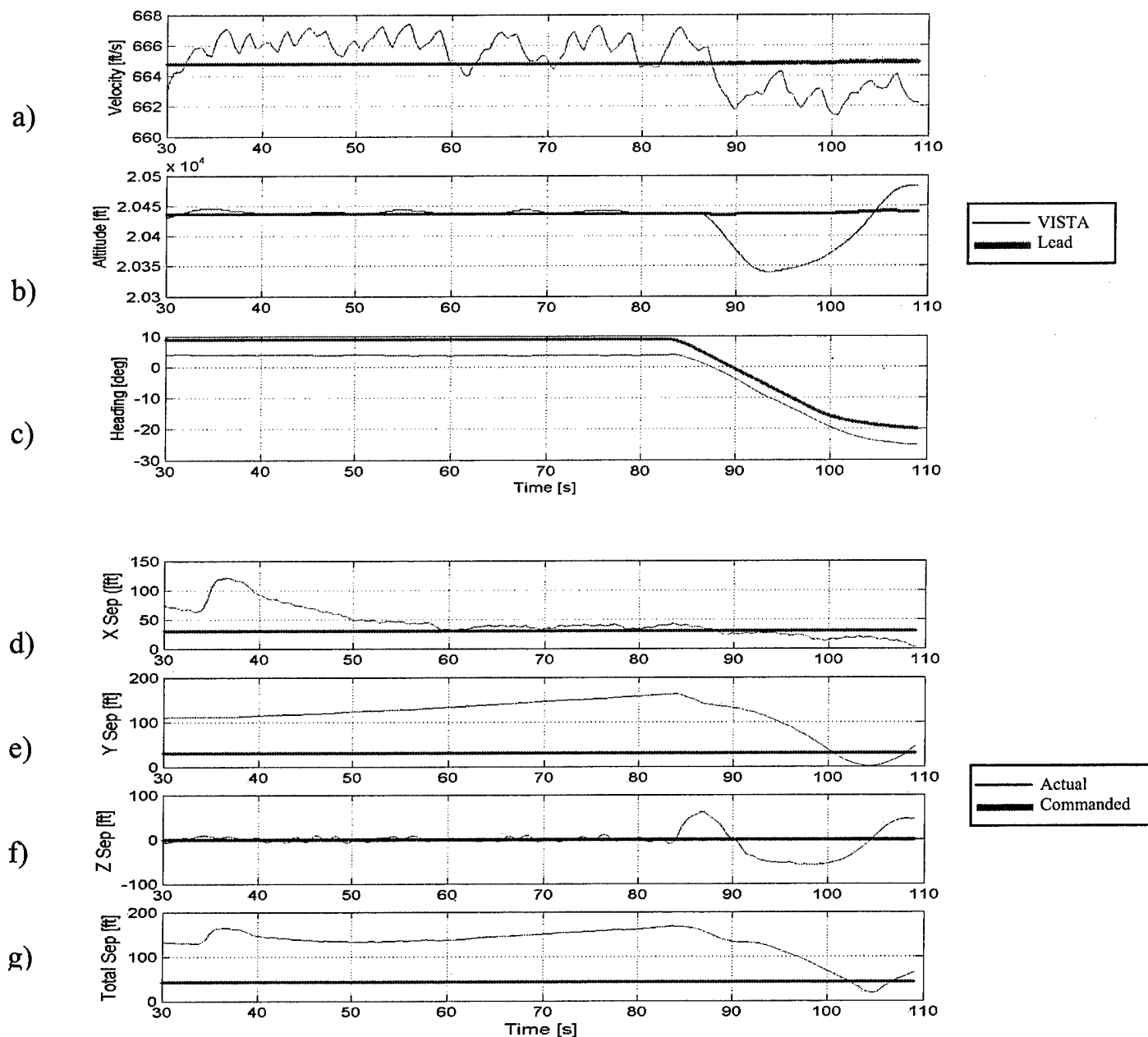
Figure 18 – Event 5B Run 1 (Sortie 1 Record 10)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	105.3	50.8	27.7	50.9
Time of maximum error (seconds)	200.0	200.0	164.7	98.3
Lead Maneuver	Turns left 30 degrees while VISTA is commanded to maintain standard position (30 30 0)			

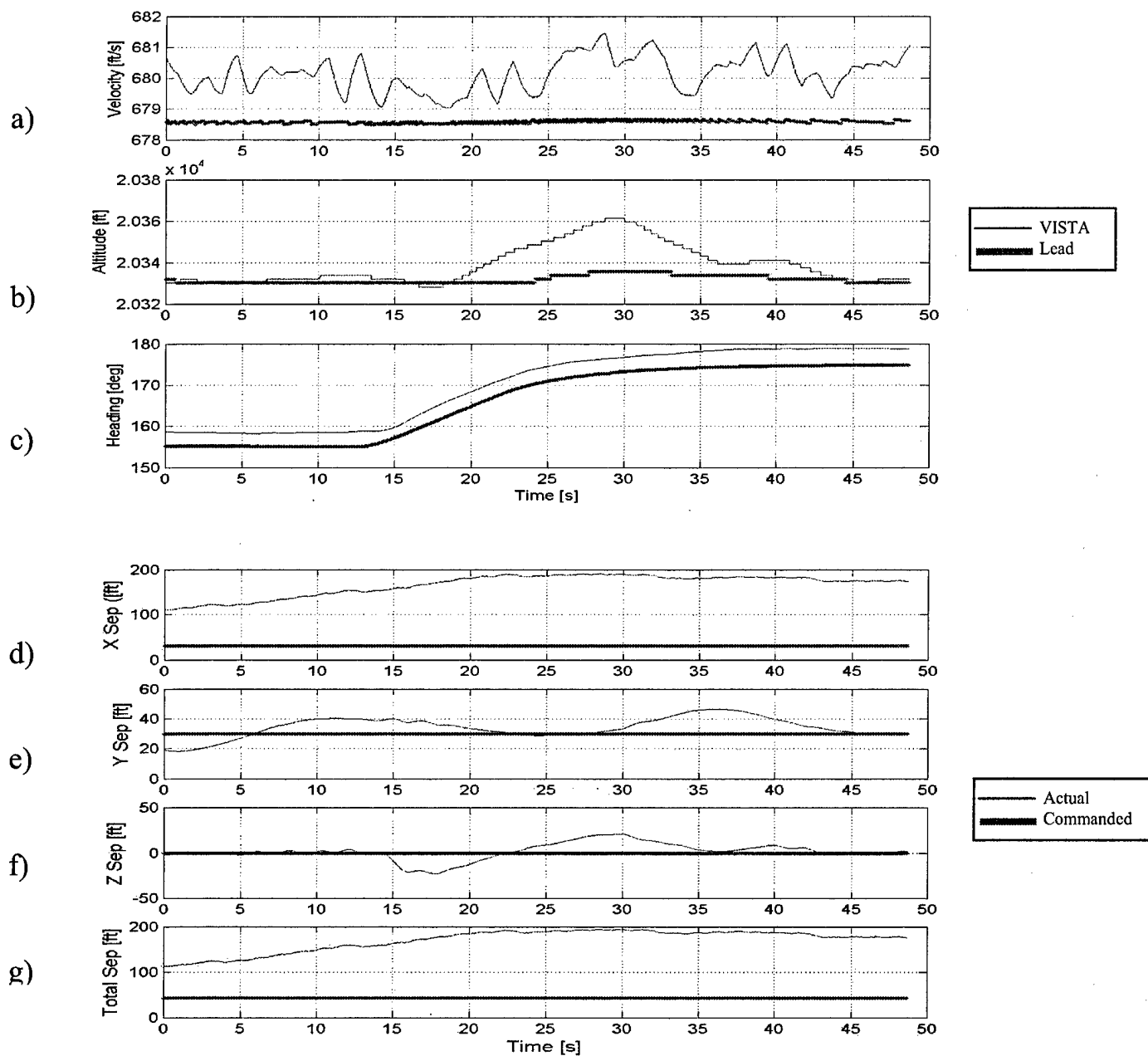
Figure 19 – Event 5C Run 1 (Sortie 1 Record 3)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	92.0	132.5	61.4	125.4
Time of maximum error (seconds)	36.8	83.9	86.8	83.6
Lead Maneuver	Turns left 30 degrees while VISTA is commanded to maintain standard position (30 30 0)			

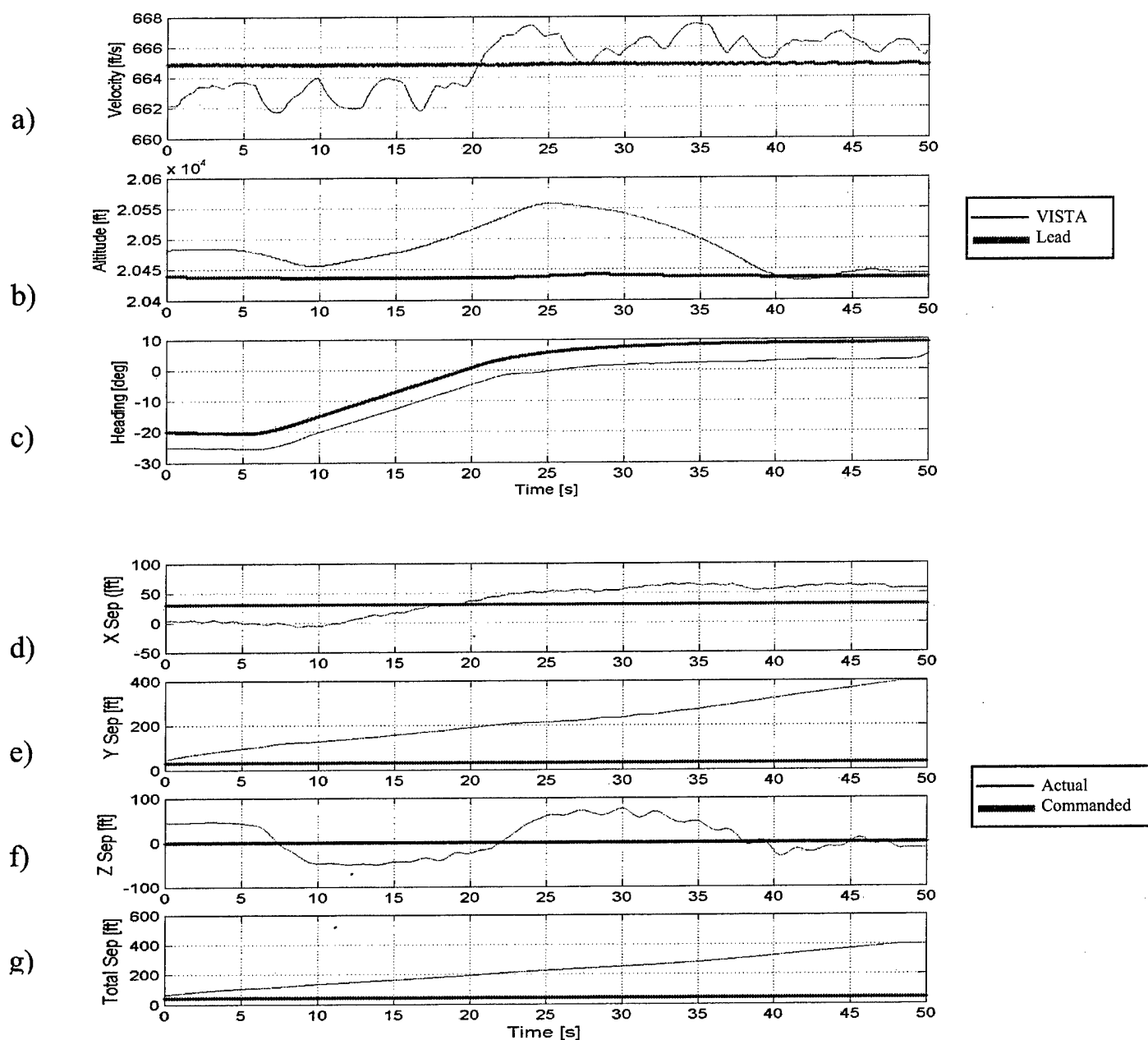
Figure 20 – Event 5C Run 2 (Sortie 1 Record 13)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	160.8	16.5	22.9	151.9
Time of maximum error (seconds)	28.5	36.0	17.7	28.5
Lead Maneuver	Turns right 20 degrees while VISTA is commanded to maintain standard position (30 30 0)			

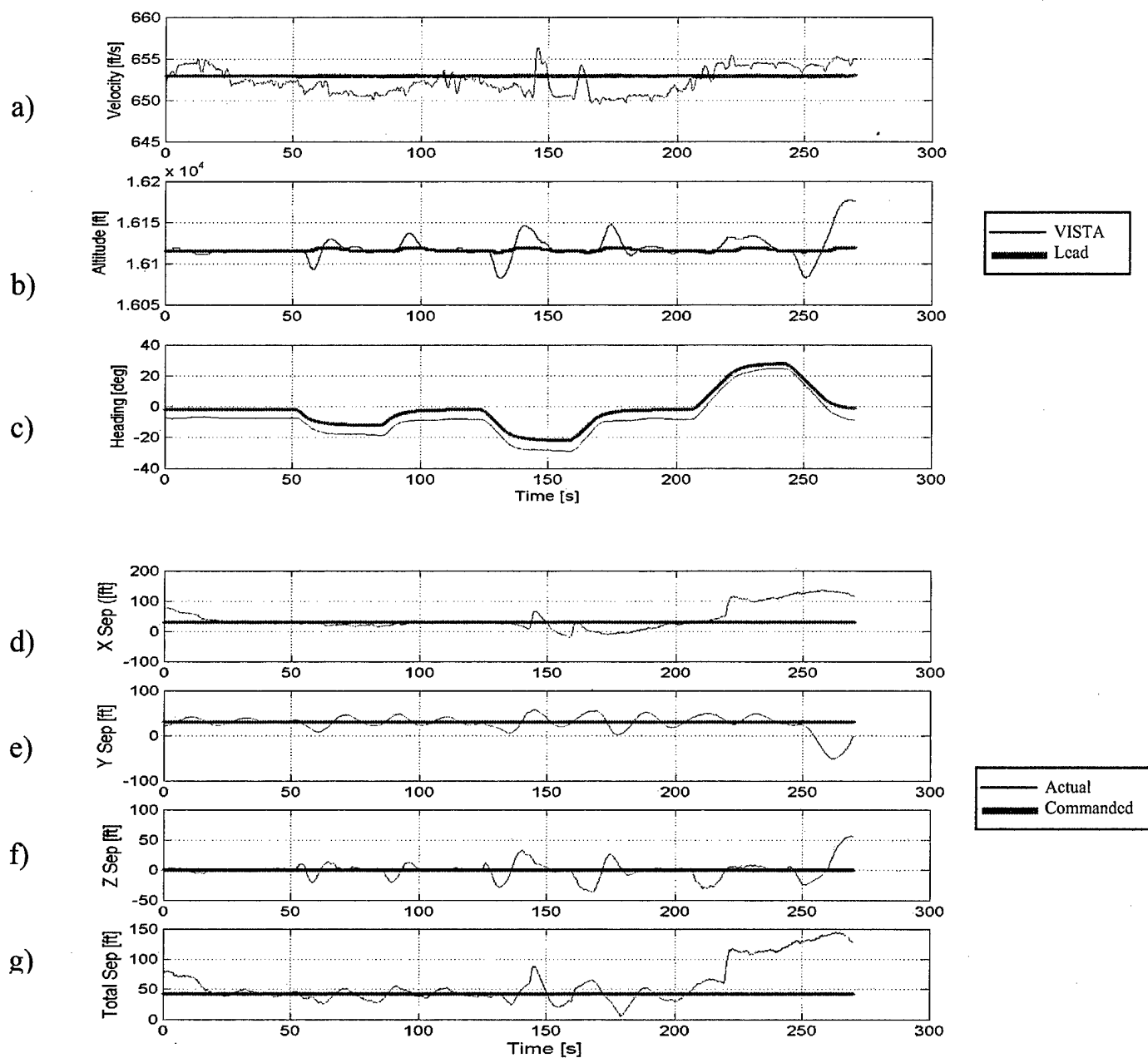
Figure 21 – Event 5E Run 1 (Sortie 1 Record 11)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	37.0	366.5	75.2	358.3
Time of maximum error (seconds)	8.7	48.5	29.9	48.5
Lead Maneuver	Turns right 30 degrees while VISTA is commanded to maintain standard position (30 30 0)			

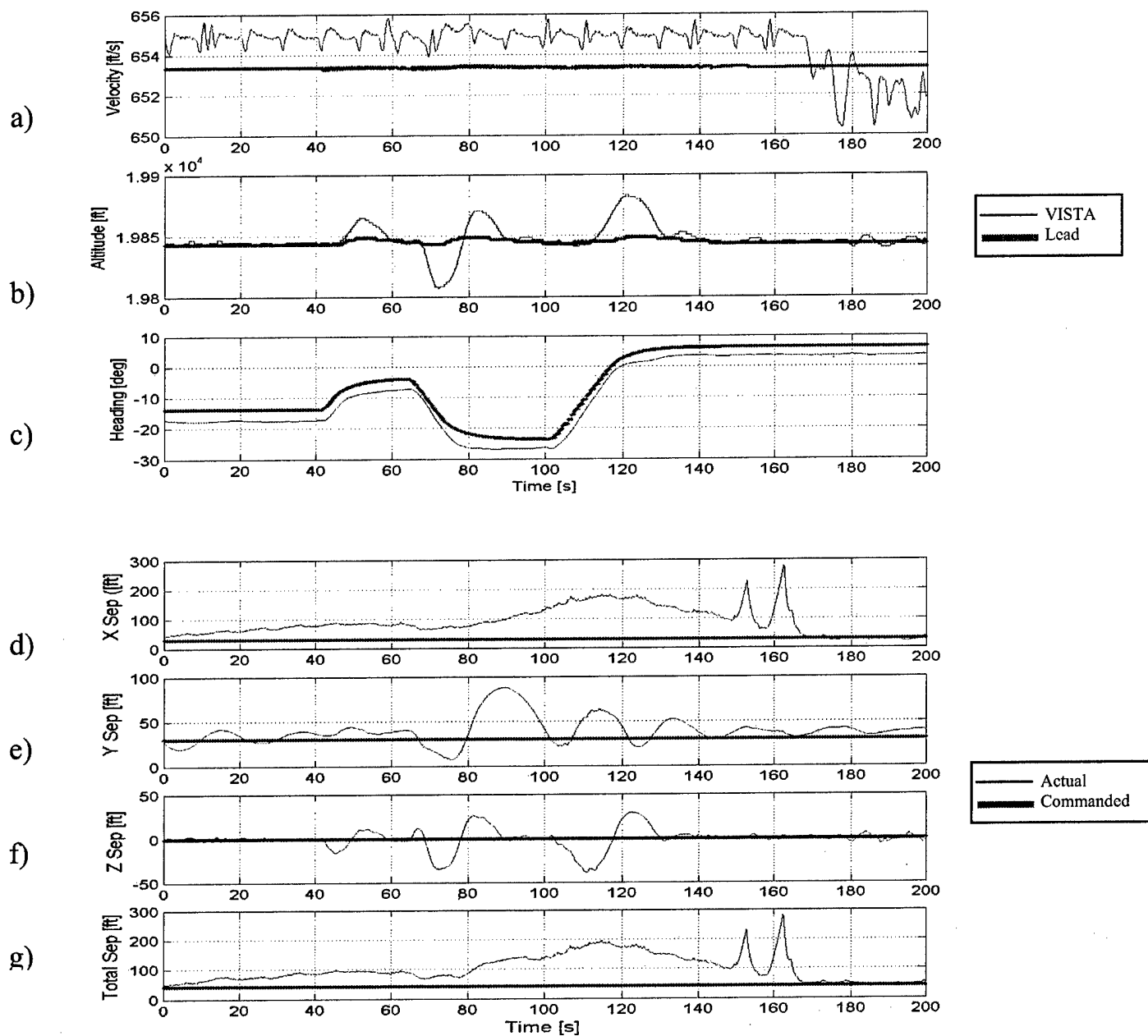
Figure 22 – Event 5F Run 1 (Sortie 1 Record 14)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		106.4	80.9	56.5	102.6
Time of maximum error (seconds)		258.1	262.0	269.3	263.4
Lead Maneuver	Turns left 10, right 10, left 20, right 20, left 30, and right 30degrees while VISTA is commanded to maintain standard position (30 30 0)				

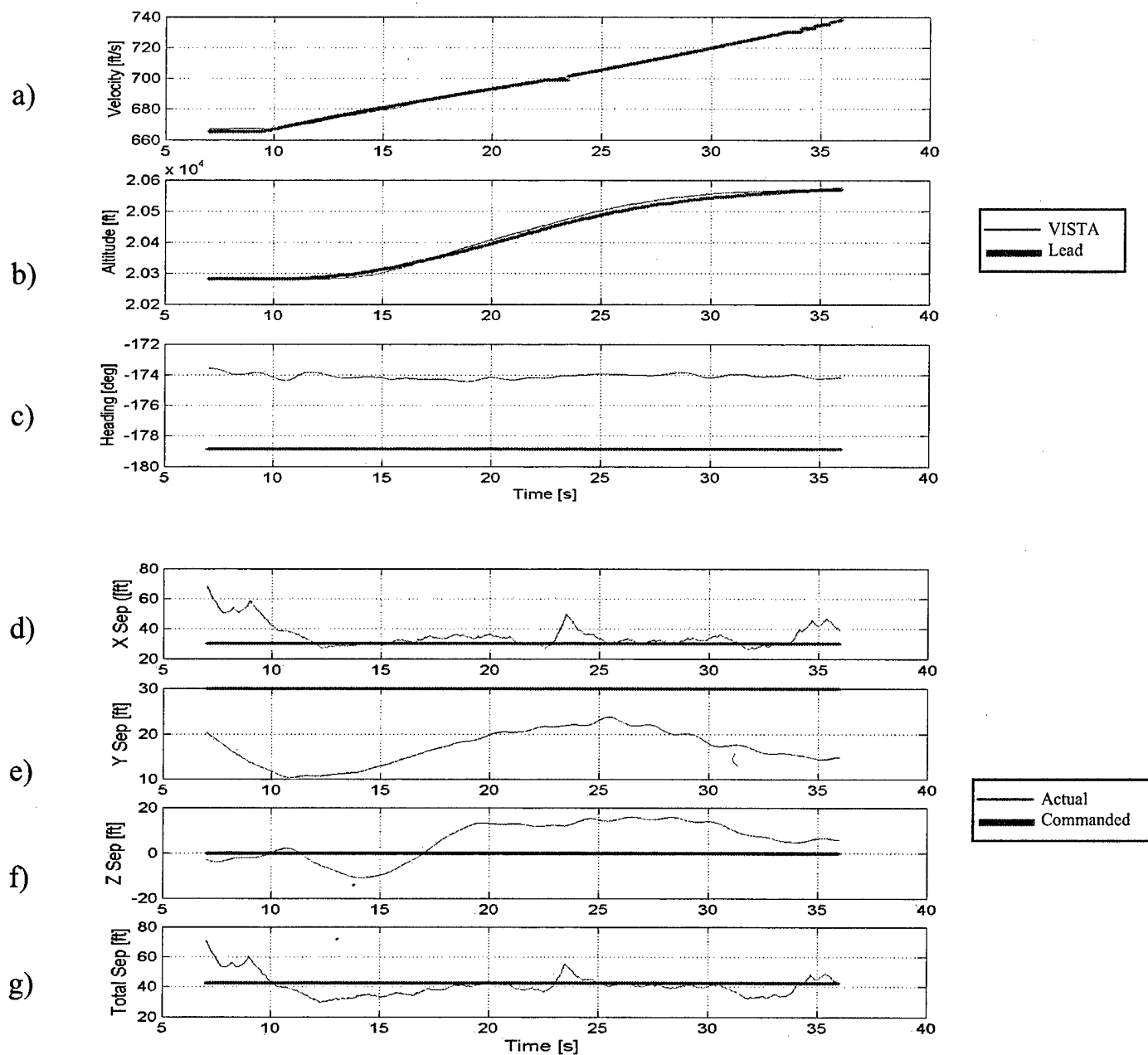
Figure 23 – Event 5A-F Run 2 (Sortie 3 Record 12)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		246.2	57.5	38.8	236.2
Time of maximum error (seconds)		162.6	89.3	111.0	162.6
Lead Maneuver	Turns left 20 degrees, right 10 degrees, right 30 degrees while VISTA is commanded to maintain standard position (30 30 0)				

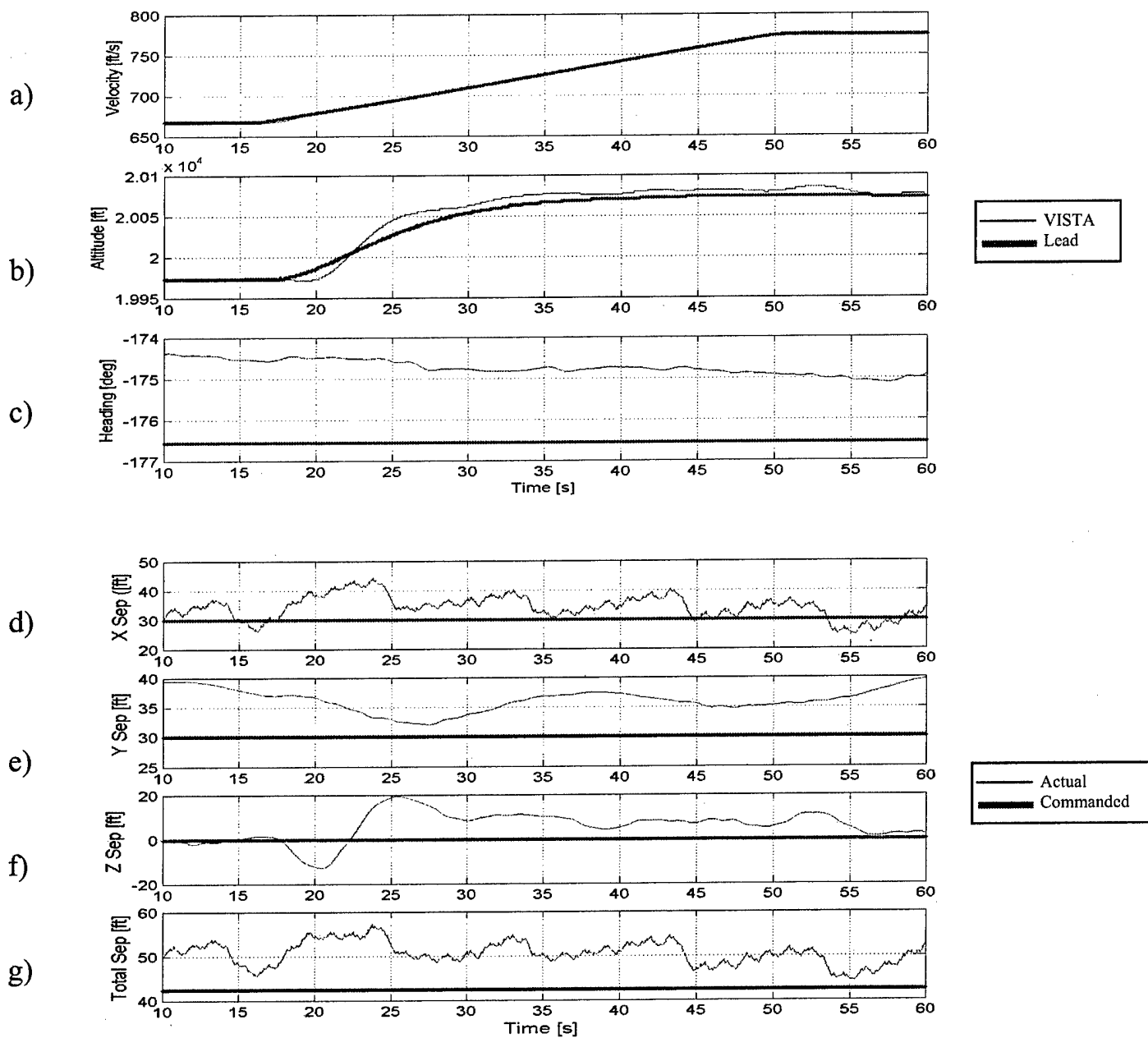
Figure 24 – Event 5B,D,F Run 3 (Sortie 4 Record 3)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	37.9	19.7	15.9	28.5
Time of maximum error (seconds)	7.0	10.8	26.6	7.0
Lead Maneuver	Climbs 300 feet and accelerates 50 knots while VISTA is commanded to maintain standard position (30 30 0)			

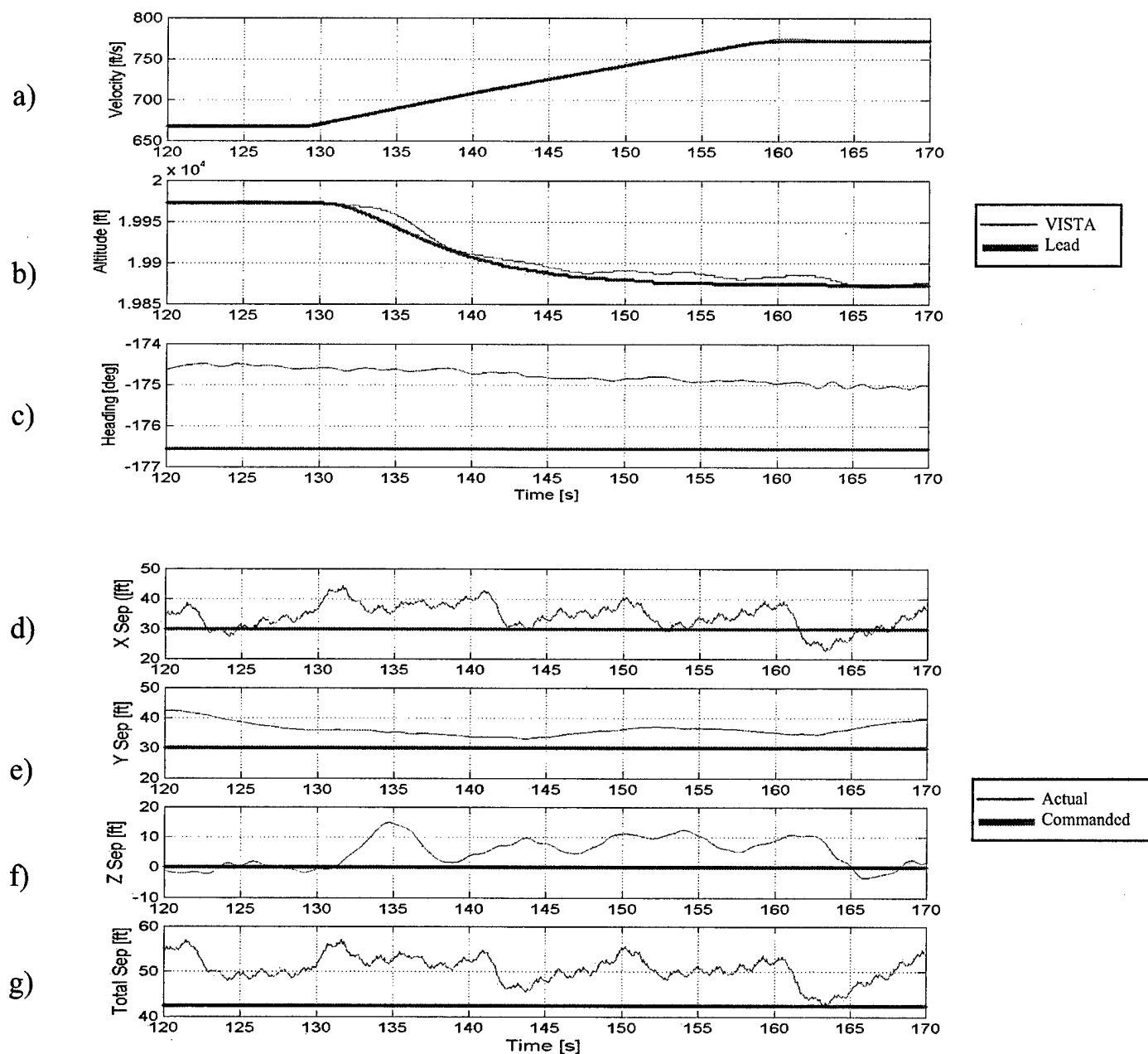
Figure 25 – Event 6A Run 1 (Sortie 1 Record 37)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		14.3	9.7	19.4	14.8
Time of maximum error (seconds)		23.8	60.0	25.4	23.8
Lead Maneuver	Climbs 100 feet and accelerates 50 knots while VISTA is commanded to maintain standard position (30 30 0)				

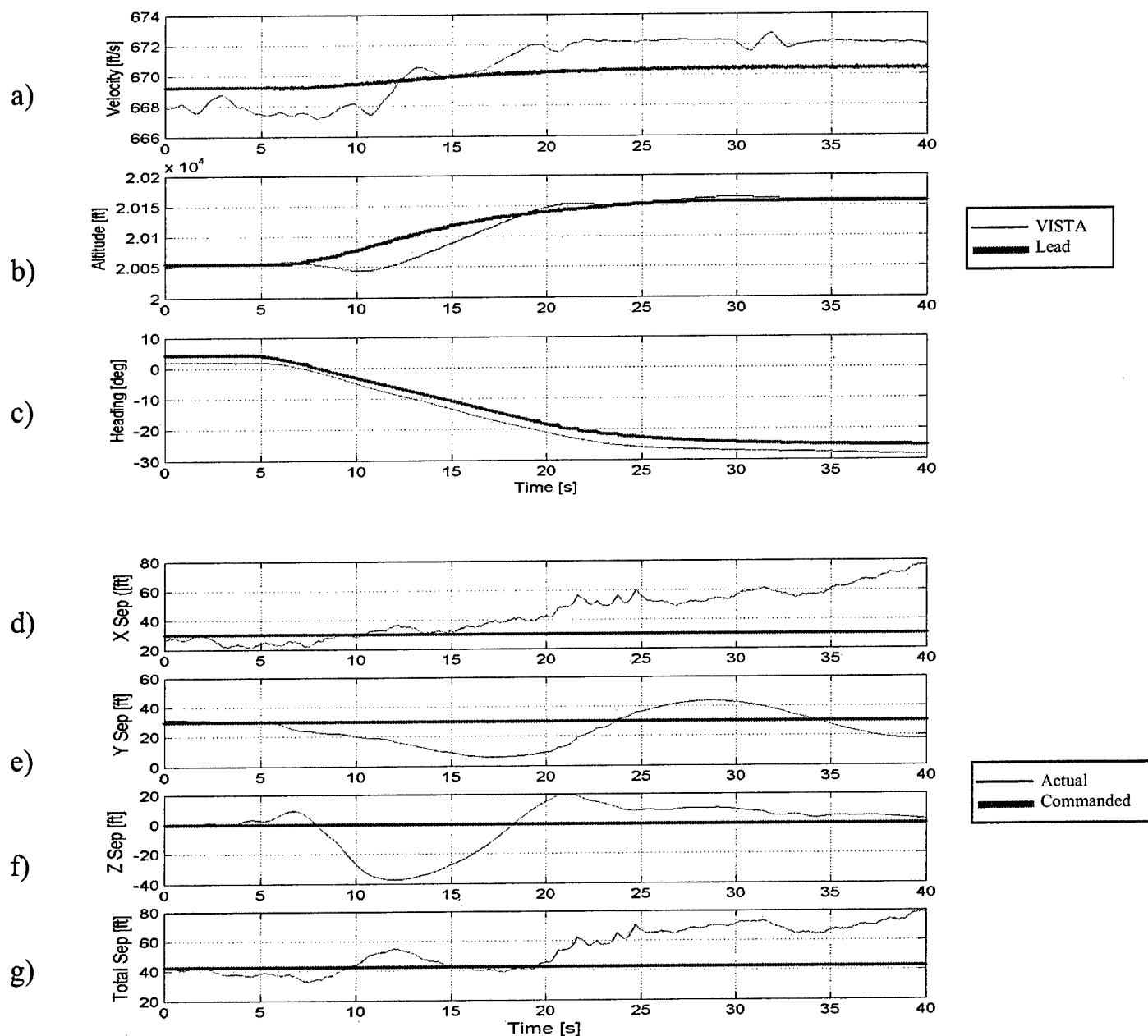
Figure 26 – Event 6A Run 2 (Sortie 4 Record 7)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	14.3	12.5	14.8	14.7
Time of maximum error (seconds)	131.6	120.0	134.8	131.6
Lead Maneuver	Descends 100 feet and accelerates 50 knots while VISTA is commanded to maintain standard (30 30 0) position			

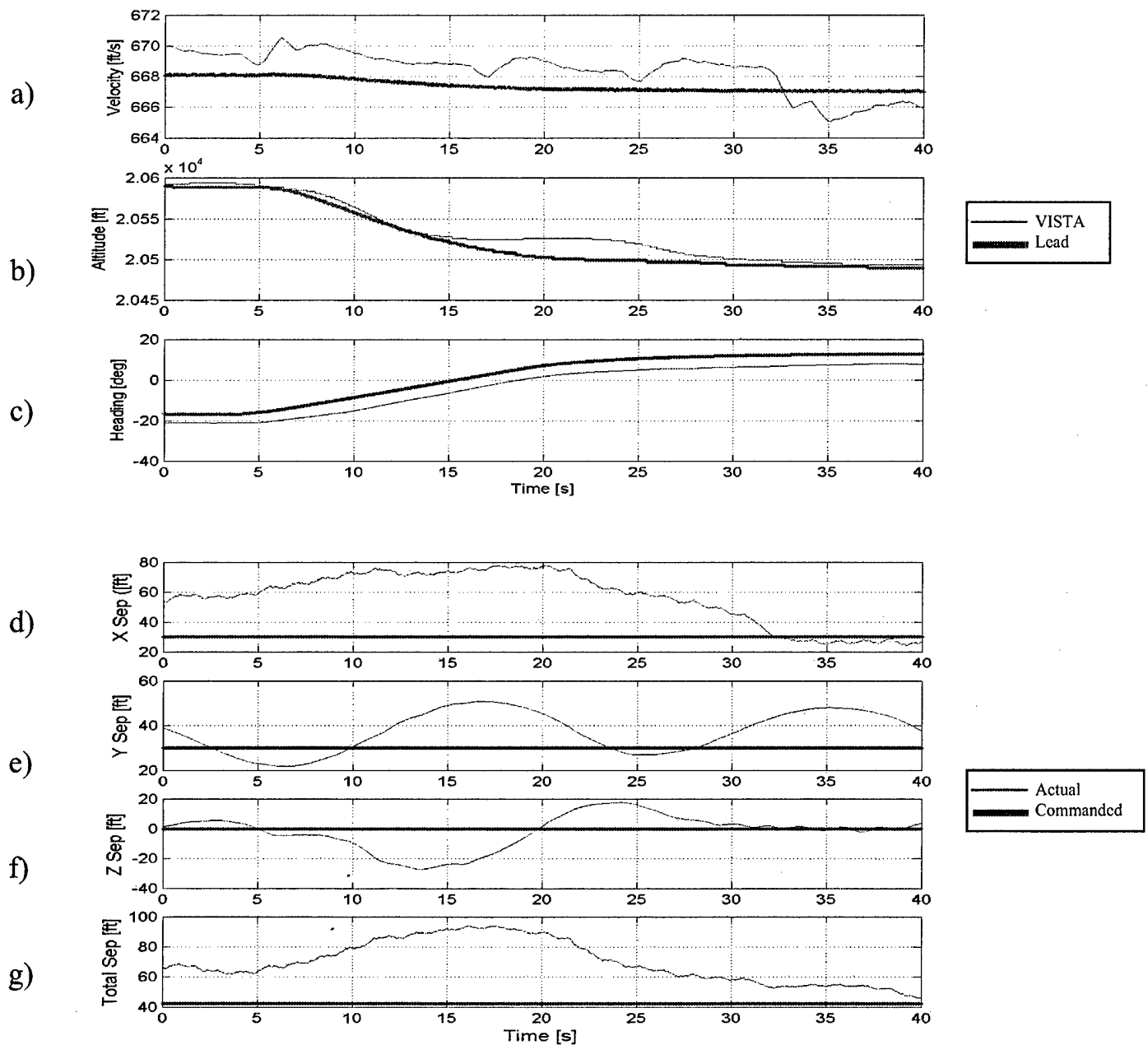
Figure 27 – Event 7A Run 1 (Sortie 4 Record 7)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	46.9	24.2	37.6	36.5
Time of maximum error (seconds)	39.6	17.3	12.0	39.6
Lead Maneuver	Climbs 100 feet and turns left 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

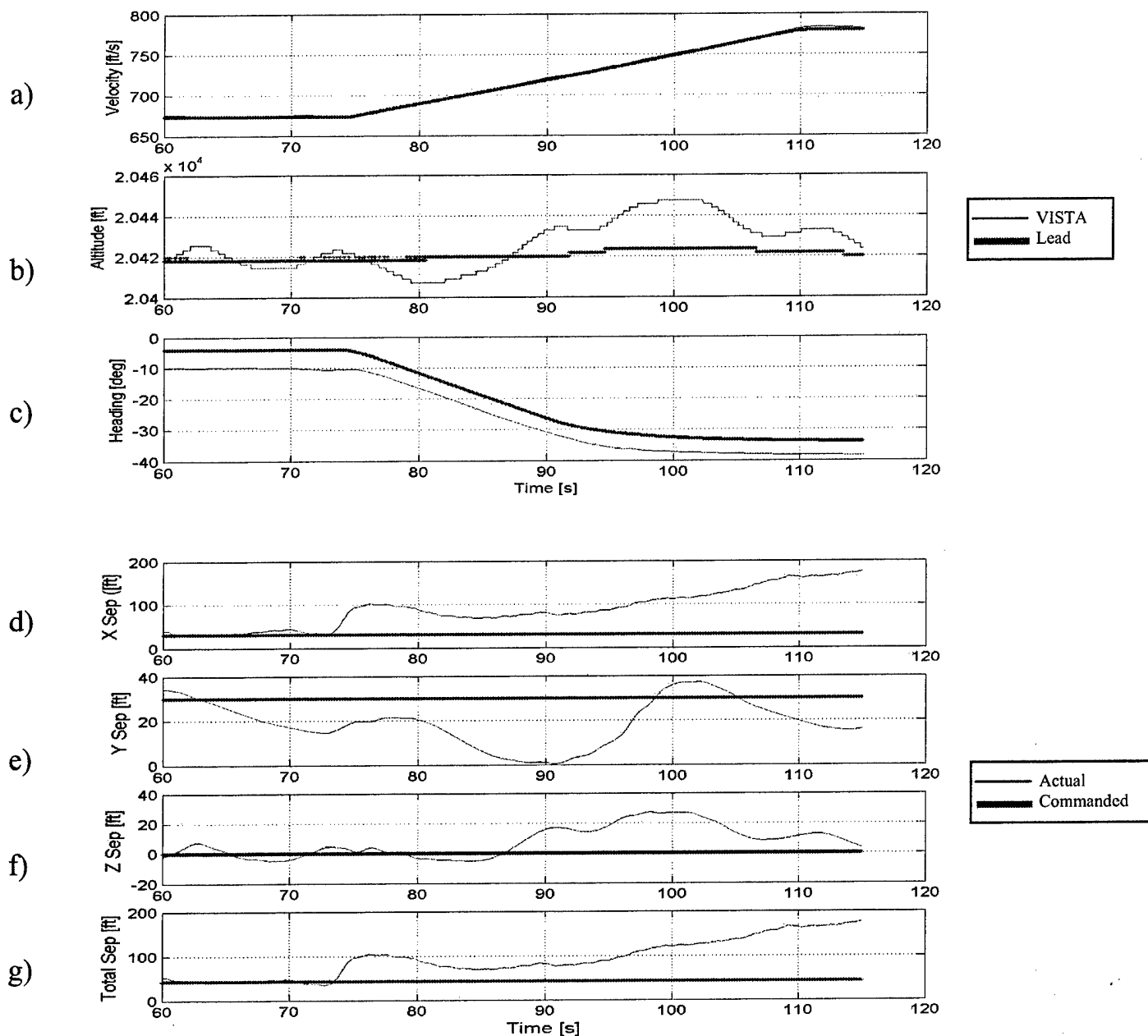
Figure 28 – Event 8A Run 1 (Sortie 4 Record 8)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	48.1	20.8	27.3	51.7
Time of maximum error (seconds)	20.2	16.8	13.5	17.4
Lead Maneuver	Descends 100 feet and turns right 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

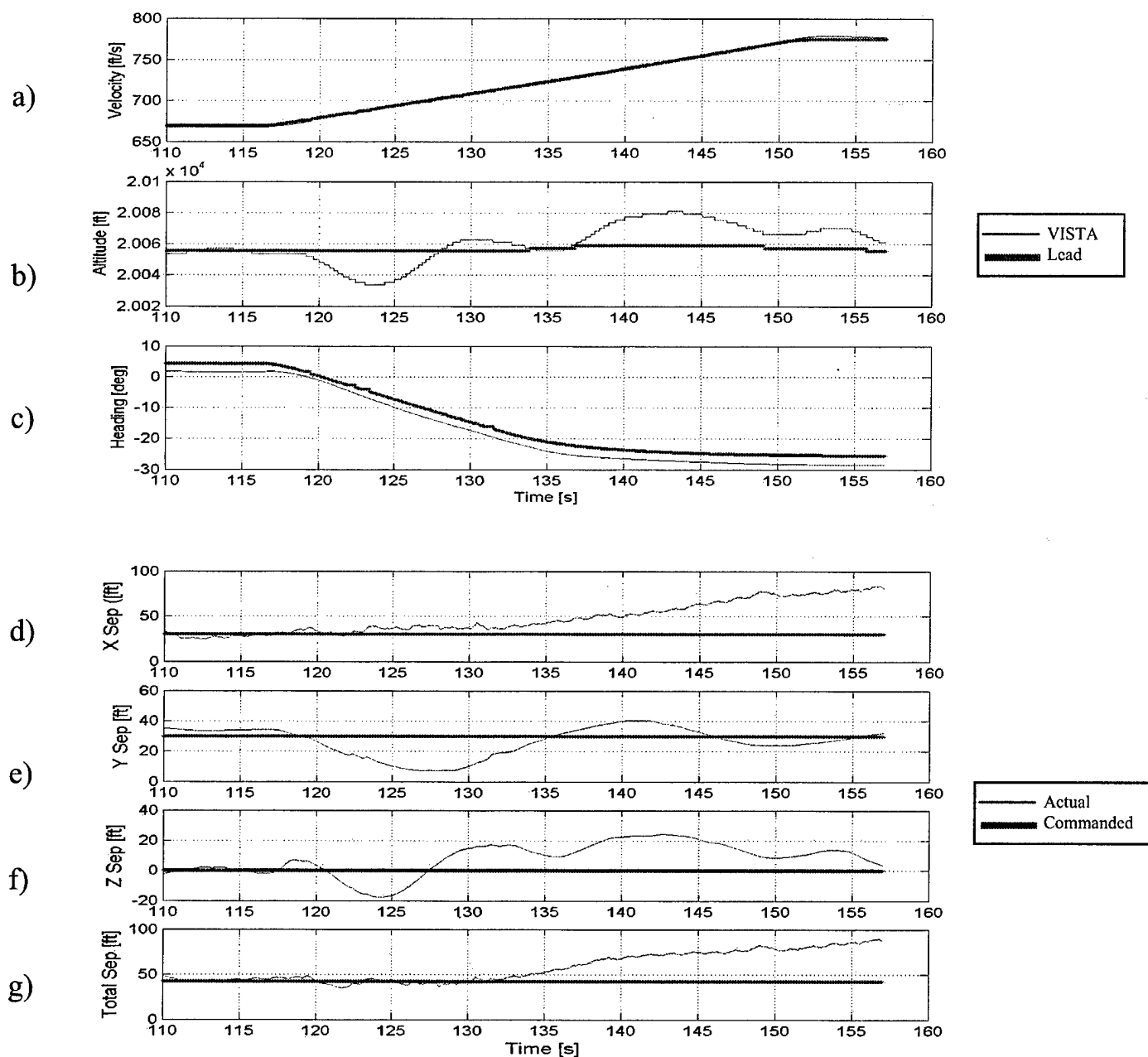
**Figure 29 – Event 8B Run 1 (Sortie 1 Record 47)**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		144.8	29.6	27.1	133.1
Time of maximum error (seconds)		115.0	90.8	98.3	115.0
Lead Maneuver	Accelerates 50 knots and turns left 30 degrees while VISTA is commanded to maintain standard (30 30 0) position				

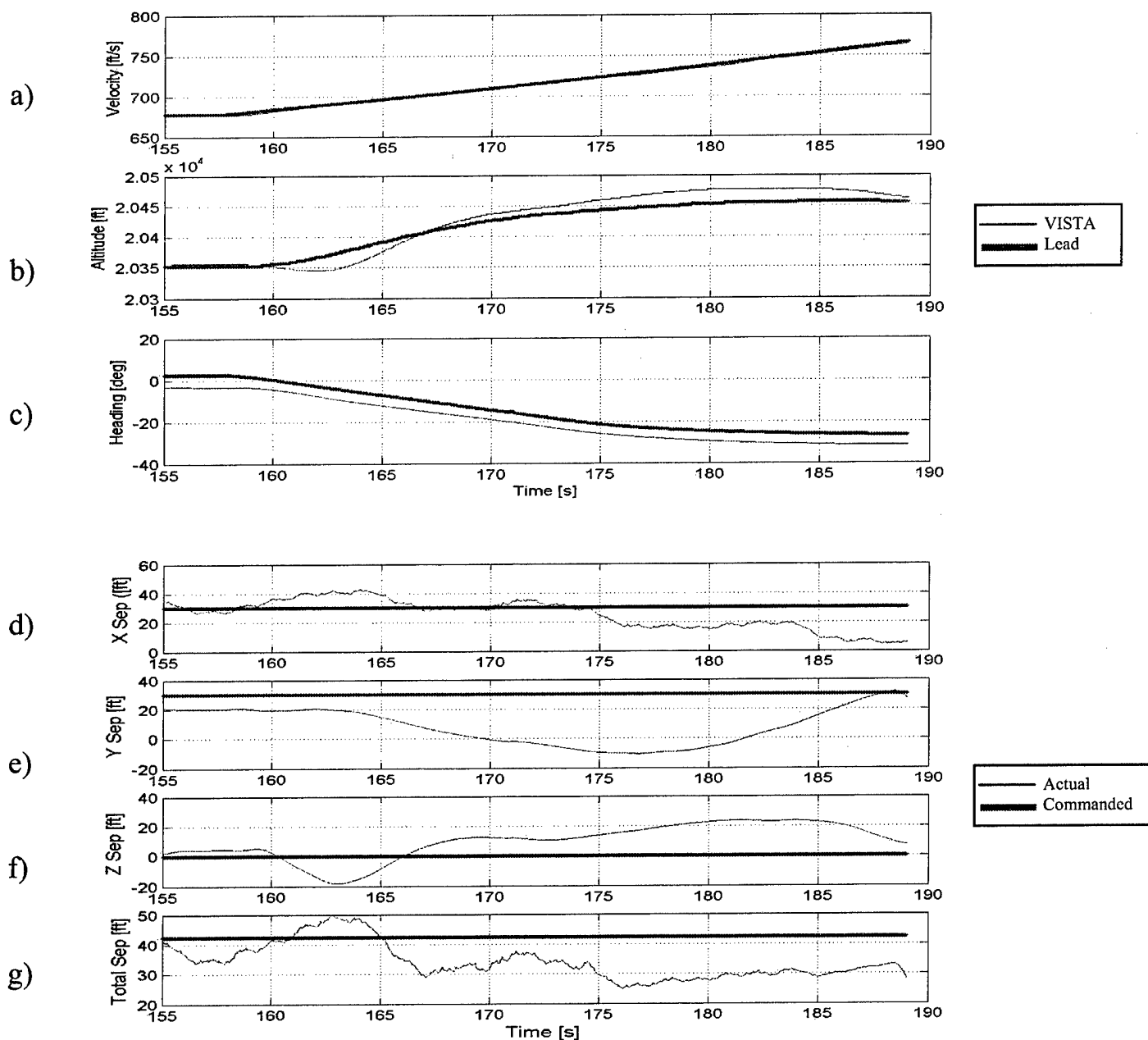
Figure 30 – Event 9A Run 1 (Sortie 2 Record 7)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	53.5	23.0	24.3	47.1
Time of maximum error (seconds)	156.8	127.1	142.7	156.8
Lead Maneuver	Accelerates 50 knots and turns left 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

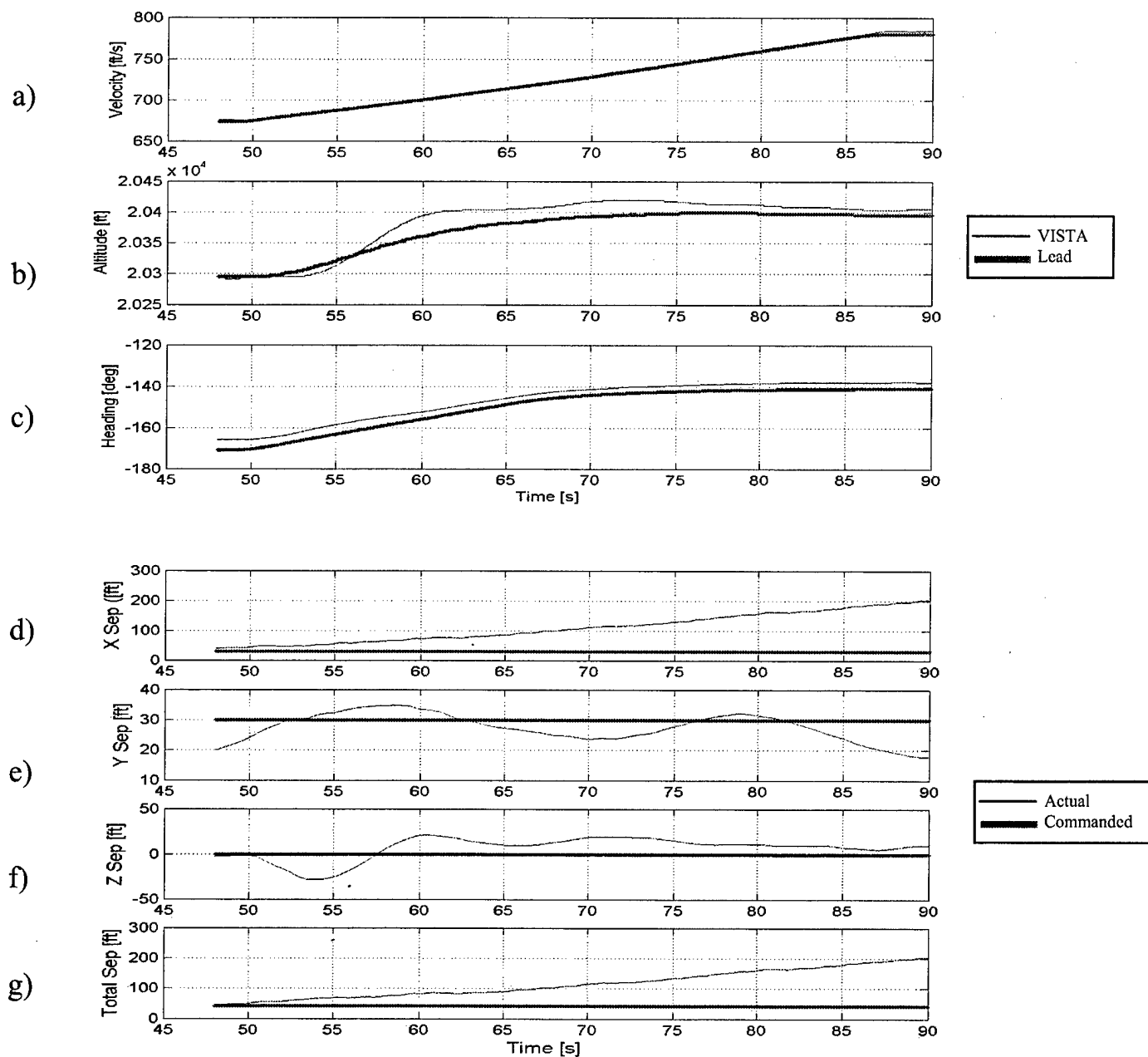
Figure 31 – Event 9A Run 2 (Sortie 4 Record 8)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	25.7	40.7	23.6	7.6
Time of maximum error (seconds)	187.9	176.7	181.5	162.8
Lead Maneuver	Climbs 100 feet, accelerates 50 knots, and turns left 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

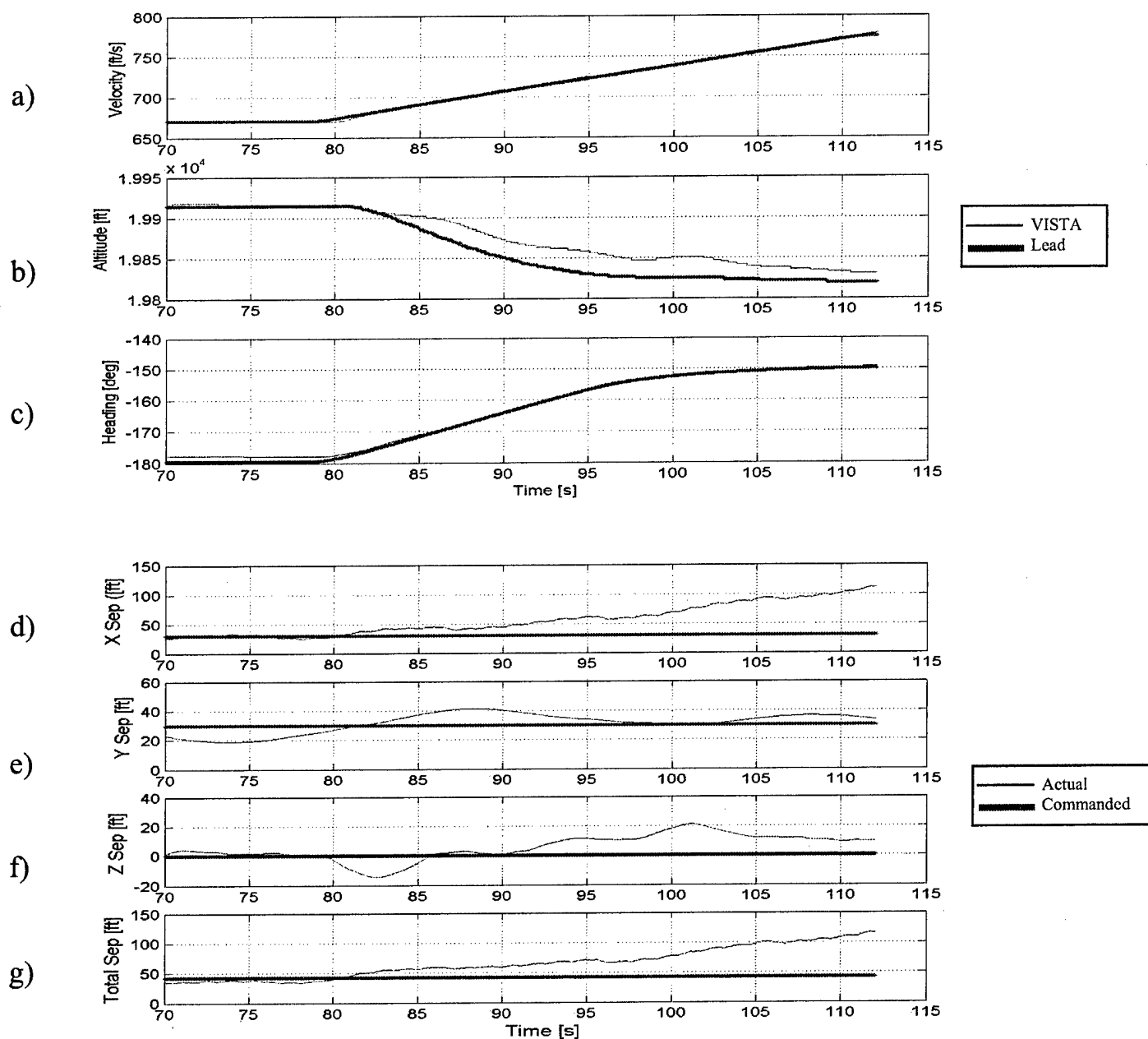
Figure 32 – Event 10A Run 1 (Sortie 2 Record 10)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	172.7	12.3	28.4	161.3
Time of maximum error (seconds)	89.8	90.0	53.8	89.8
Lead Maneuver	Climbs 100 feet, accelerates 50 knots, and turns right 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

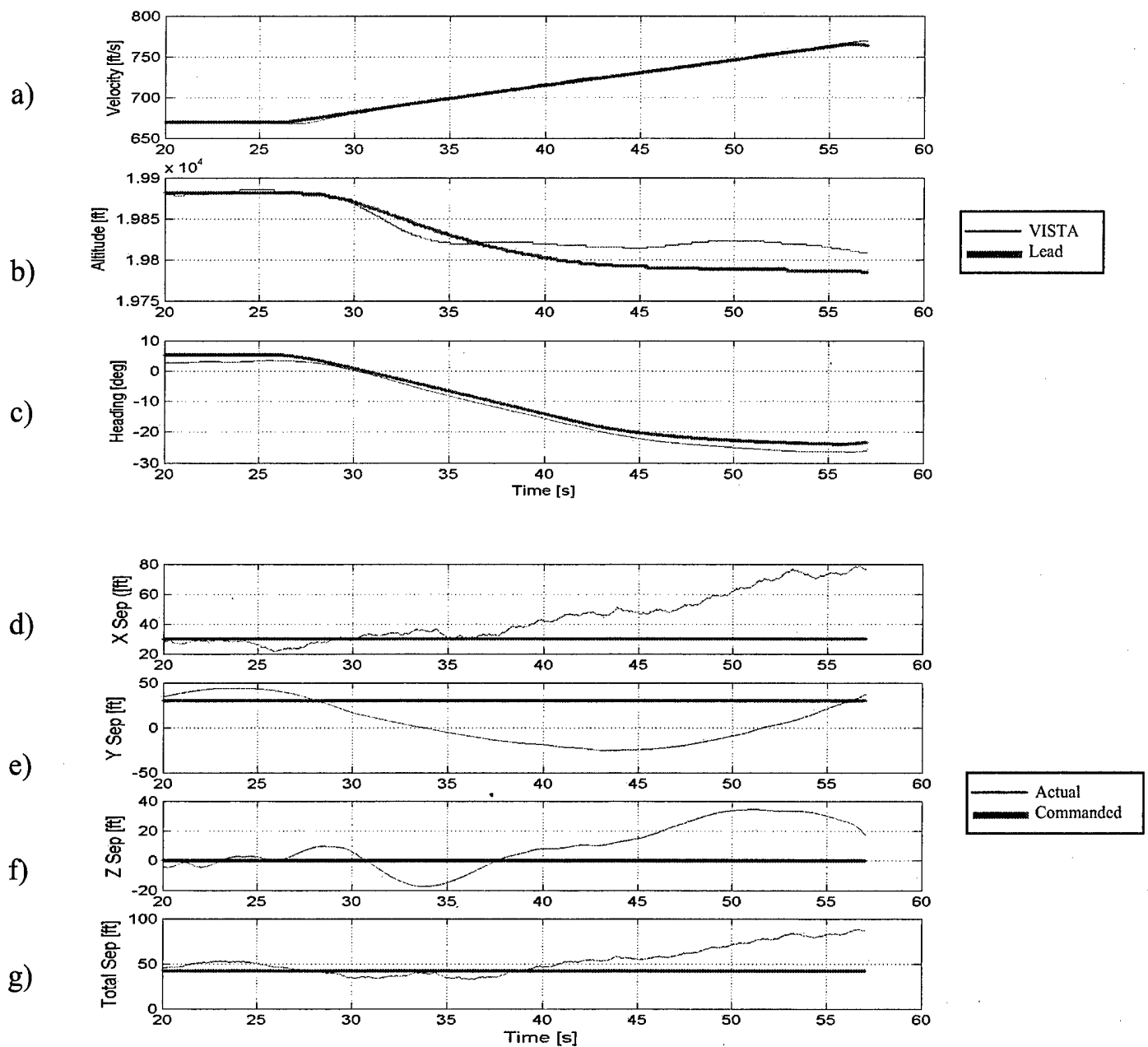
Figure 33 – Event 12A Run 1 (Sortie 2 Record 13)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	81.6	11.3	21.0	74.5
Time of maximum error (seconds)	111.7	88.6	101.2	111.7
Lead Maneuver	Descends 100 feet, accelerates 50 knots, and turns right 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

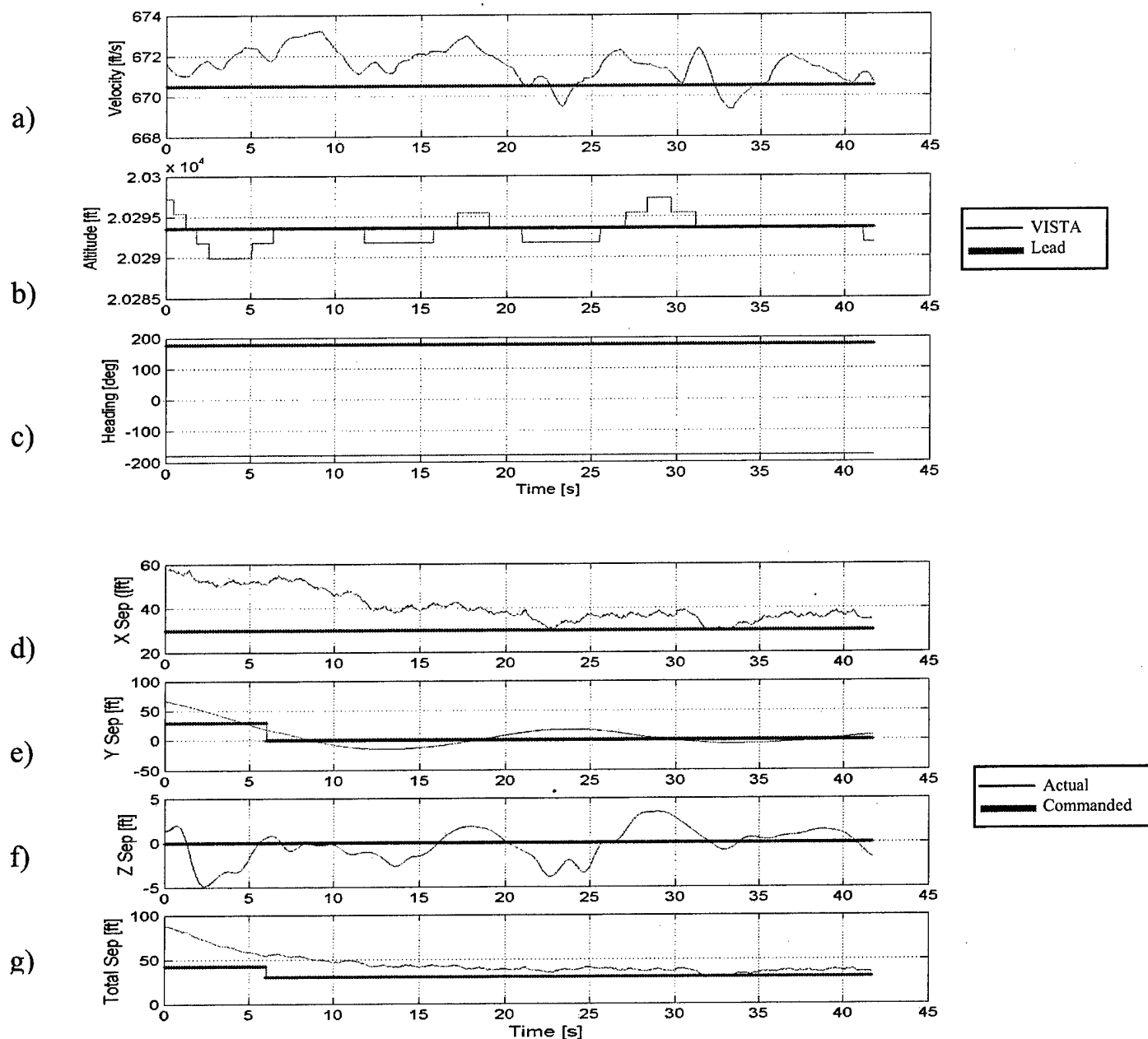
Figure 34 – Event 12B Run 1 (Sortie 4 Record 13)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	48.9	55.5	34.5	46.0
Time of maximum error (seconds)	56.7	43.4	51.1	56.7
Lead Maneuver	Descends 100 feet, accelerates 50 knots, and turns left 30 degrees while VISTA is commanded to maintain standard (30 30 0) position			

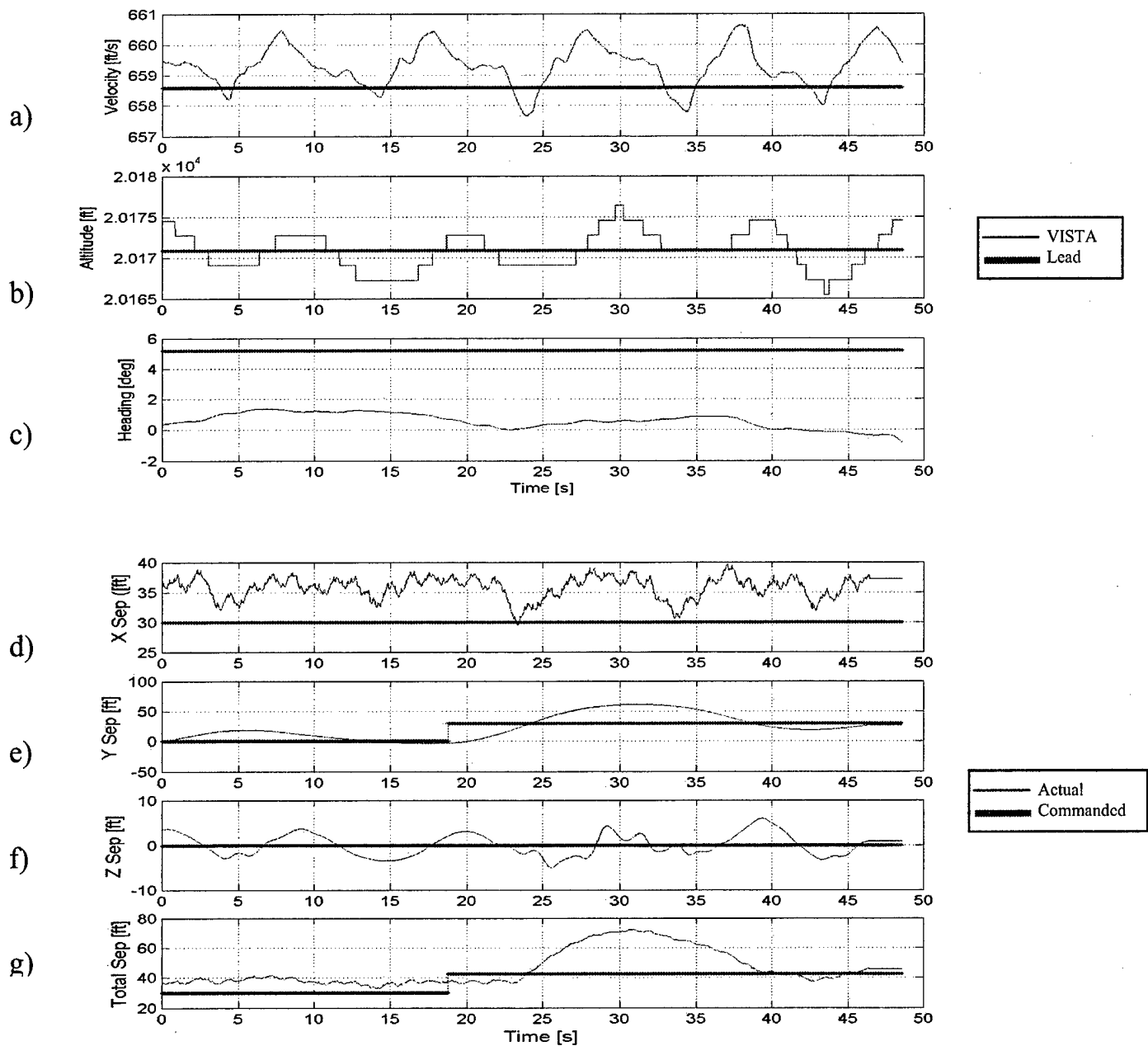
Figure 35 – Event 13B Run 1 (Sortie 4 Record 14)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	28.2	37.4	4.9	45.9
Time of maximum error (seconds)	0.3	0	2.4	0
Position Change	VISTA moves right 30 feet to (30 0 0) from standard position (30 30 0)			

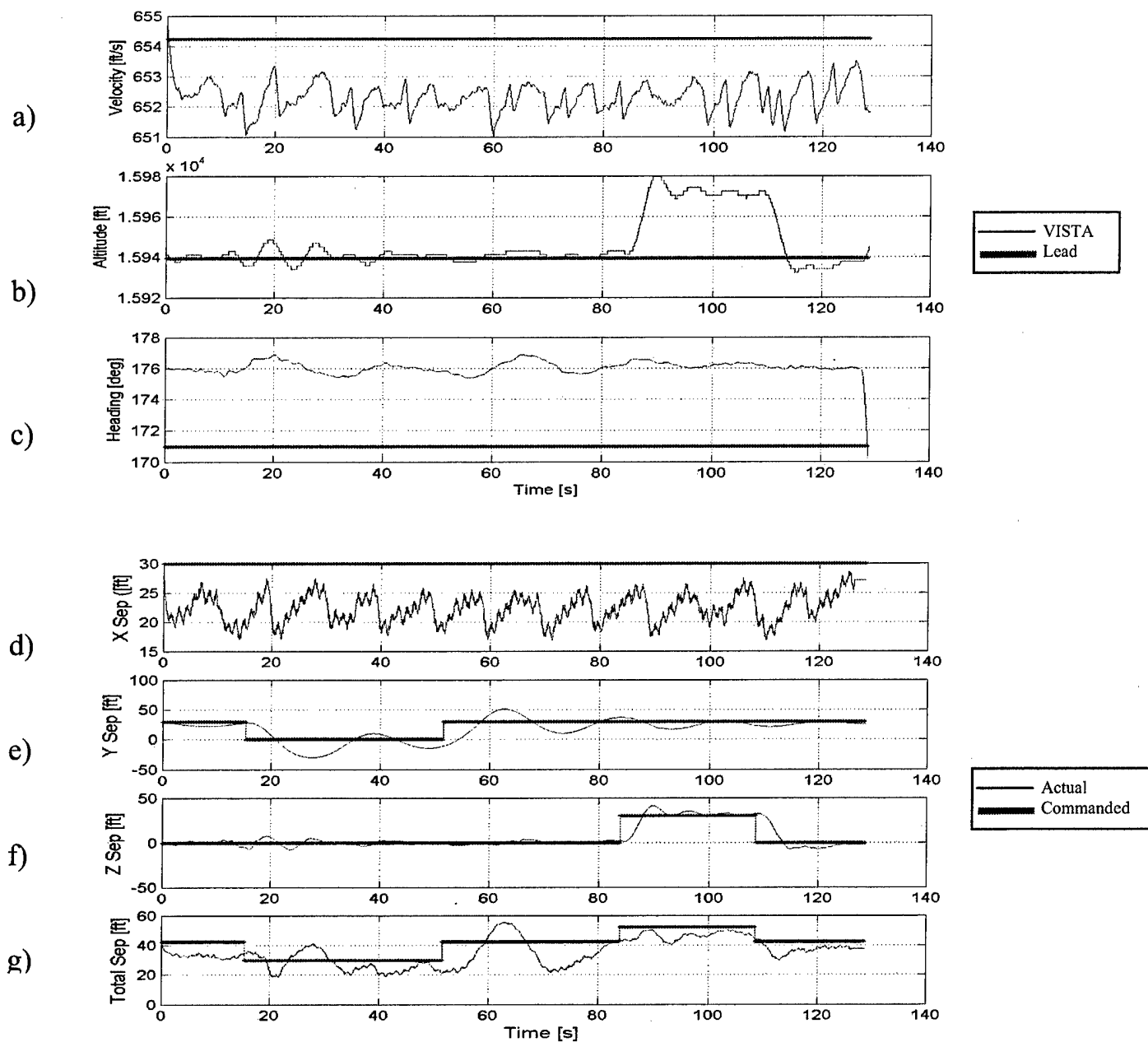
Figure 36 – Event 14A Run 1 (Sortie 1 Record 16)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	9.6	33.0	6.0	29.7
Time of maximum error (seconds)	37.0	18.8	39.4	30.8
Position Change	VISTA moves left 30 feet from (30 0 0) back to standard position (30 30 0)			

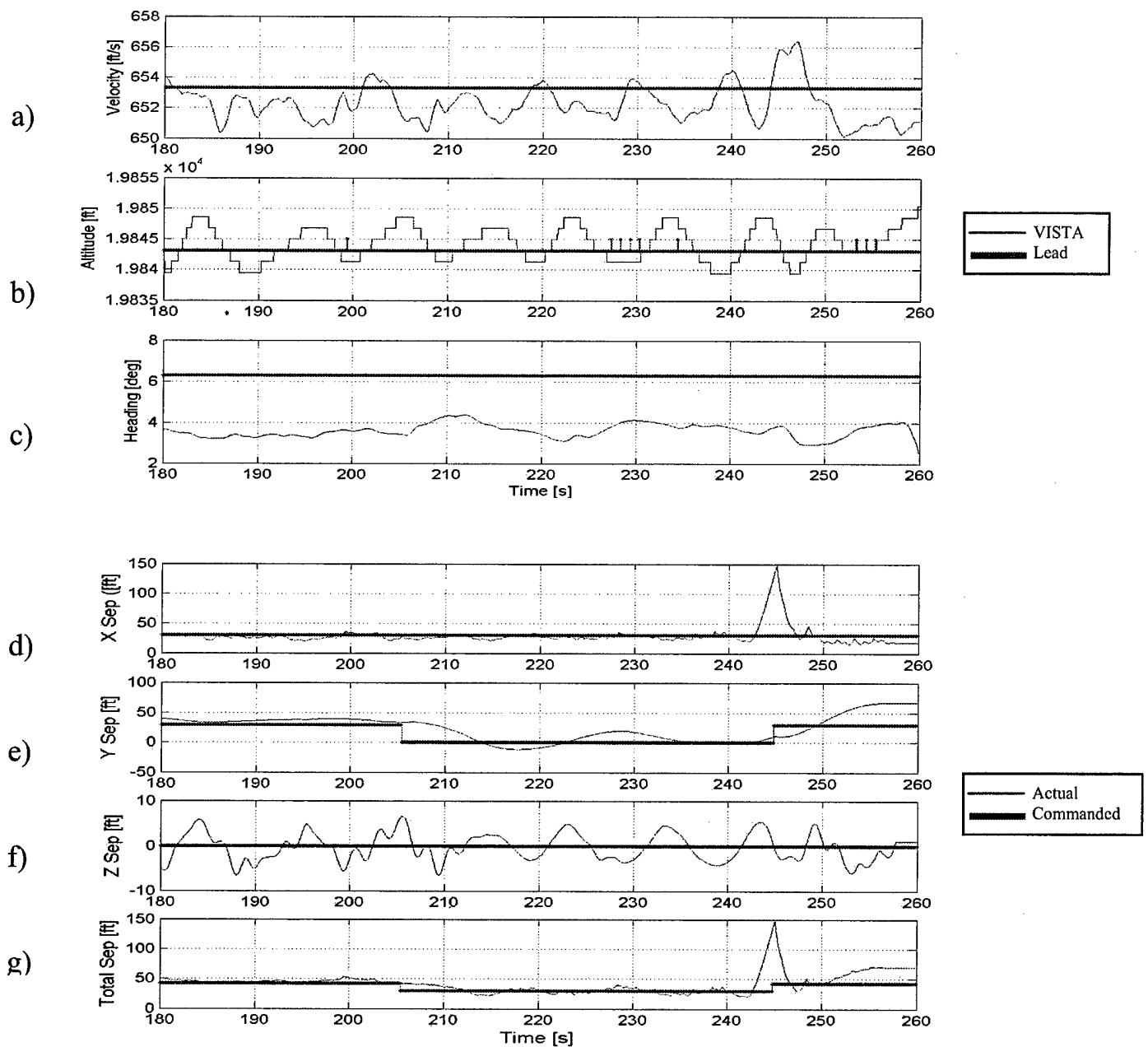
Figure 37 – Event 14B Run 1 (Sortie 1 Record 21)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	13.2	41.2	32.1	13.3
Time of maximum error (seconds)	71.3	51.5	108.8	62.8
Position Change	VISTA moves right 30 feet to (30 0 0) from standard position (30 30 0) and then back to standard position (30 30 0)			

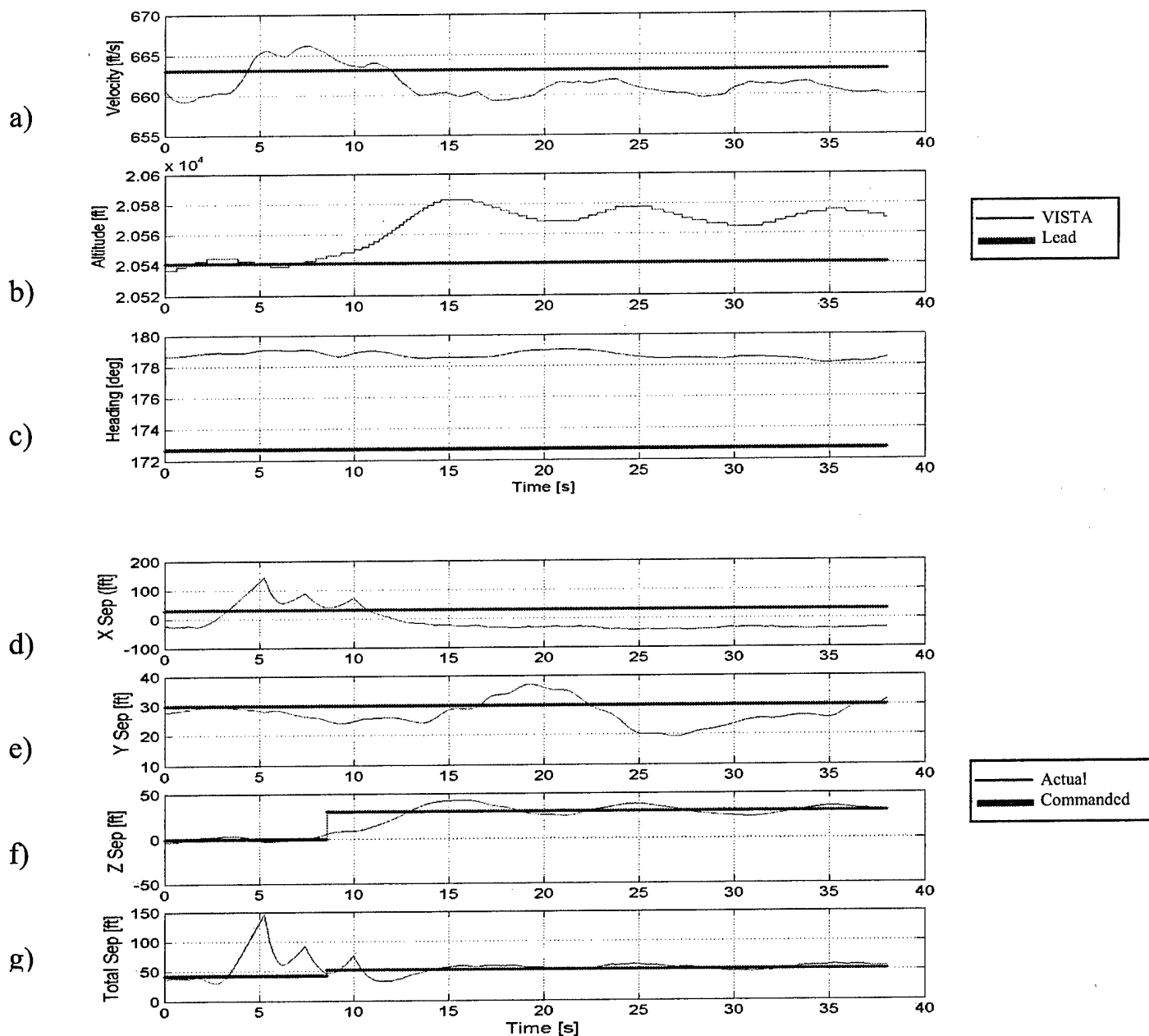
**Figure 38 – Event 14A & B Run 2 (Sortie 3 Record 13)**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	117.5	37.2	6.6	105.5
Time of maximum error (seconds)	245.0	256.7	188.0	245.0
Position Change	VISTA moves right 30 feet to (30 0 0) from standard position (30 30 0) and then back to standard position (30 30 0)			

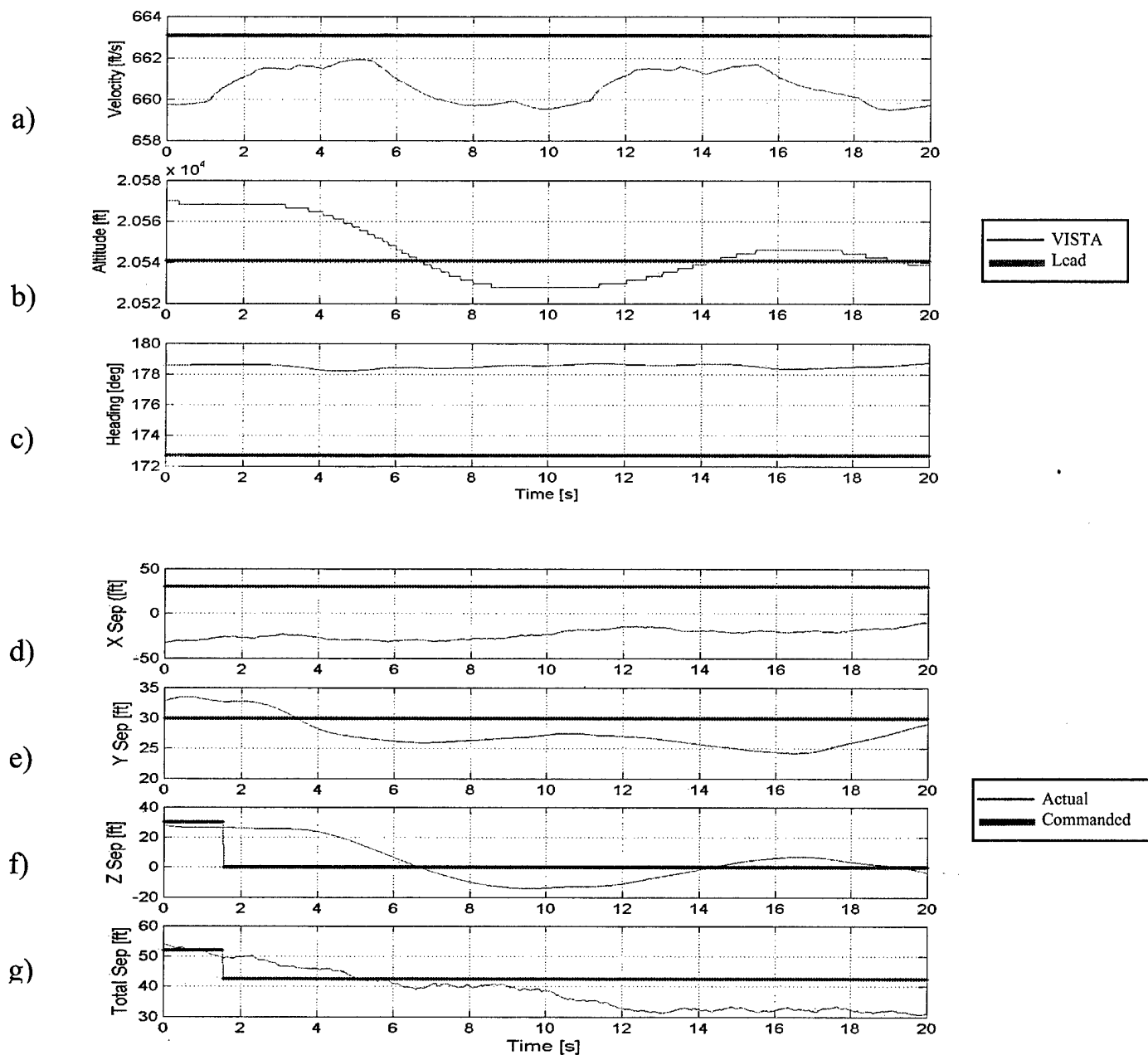
Figure 39 – Event 14A & B Run 3 (Sortie 4 Record 3)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	72.8	10.9	24.6	8.9
Time of maximum error (seconds)	5.3	26.9	8.6	24.8
Position Change	VISTA climbs 30 feet to (30 30 -30) from standard (30 30 0) position			

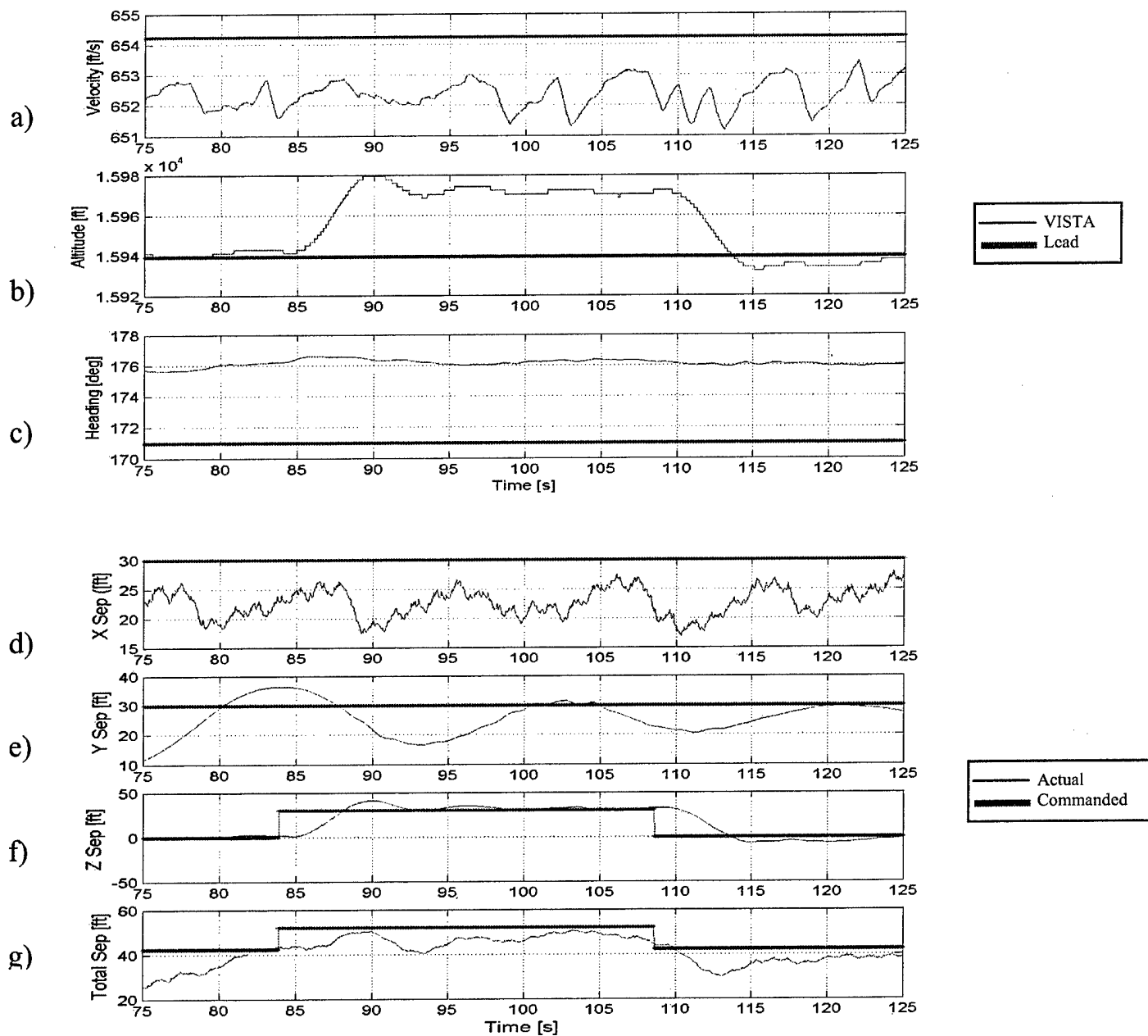
Figure 40 – Event 15A Run 1 (Sortie 2 Record 5)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	62.7	5.8	26.5	2.1
Time of maximum error (seconds)	0	16.5	1.6	0
Position Change	VISTA descends 30 feet from (30 30 30) back to standard (30 30 0) position			

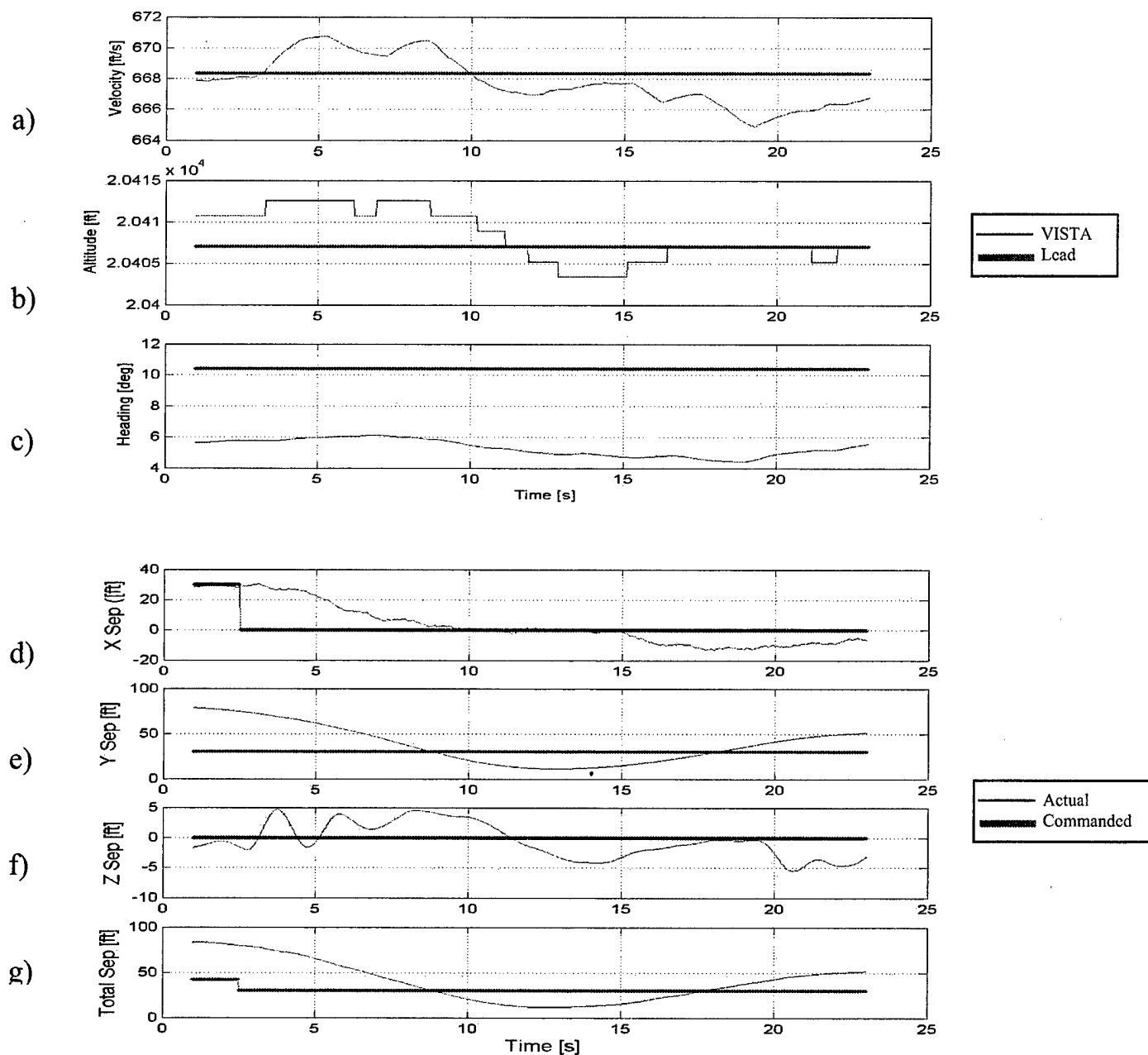
Figure 41 – Event 15B Run 1 (Sortie 2 Record 6)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		13.1	13.5	32.1	12.7
Time of maximum error (seconds)		110.3	93.2	108.8	113.1
Position Change	VISTA climbs 30 feet to (30 30 30) from standard (30 30 0) position and then descends back to standard position (30 30 0)				

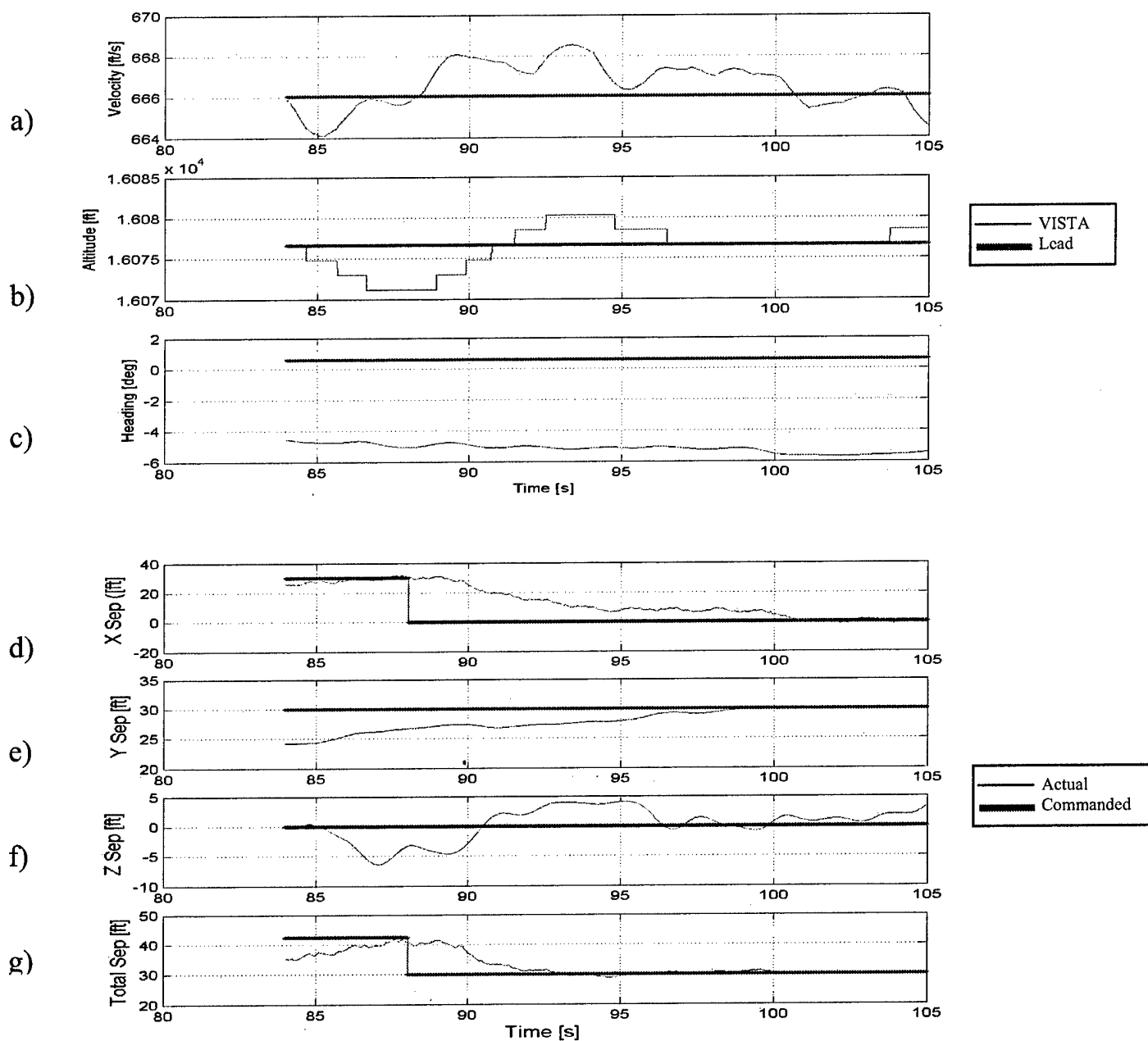
**Figure 42 – Event 15A & B Run 2 (Sortie 3 Record 13)**



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	30.5	48.6	5.5	41.2
Time of maximum error (seconds)	3.1	1.0	20.6	1.1
Position Change	VISTA moves forward 30 feet to (0 30 0) from standard position (30 30 0)			

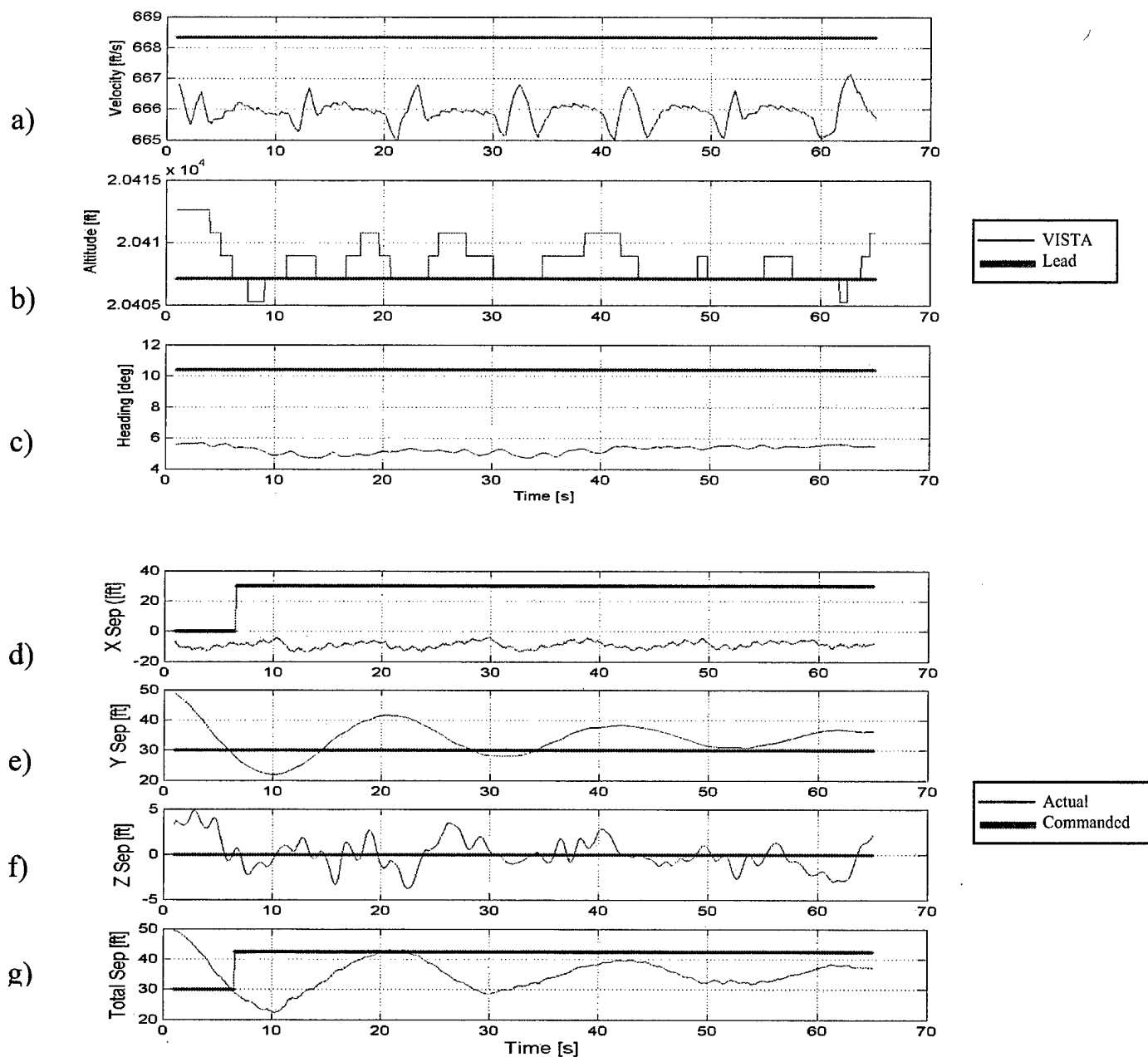
Figure 43 – Event 16A Run 1 (Sortie 1 Record 31)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	31.0	5.8	6.4	30.5
Time of maximum error (seconds)	89.0	84.0	87.1	87.6
Position Change	VISTA moves forward 30 feet to (0 30 0) from standard position (30 30 0)			

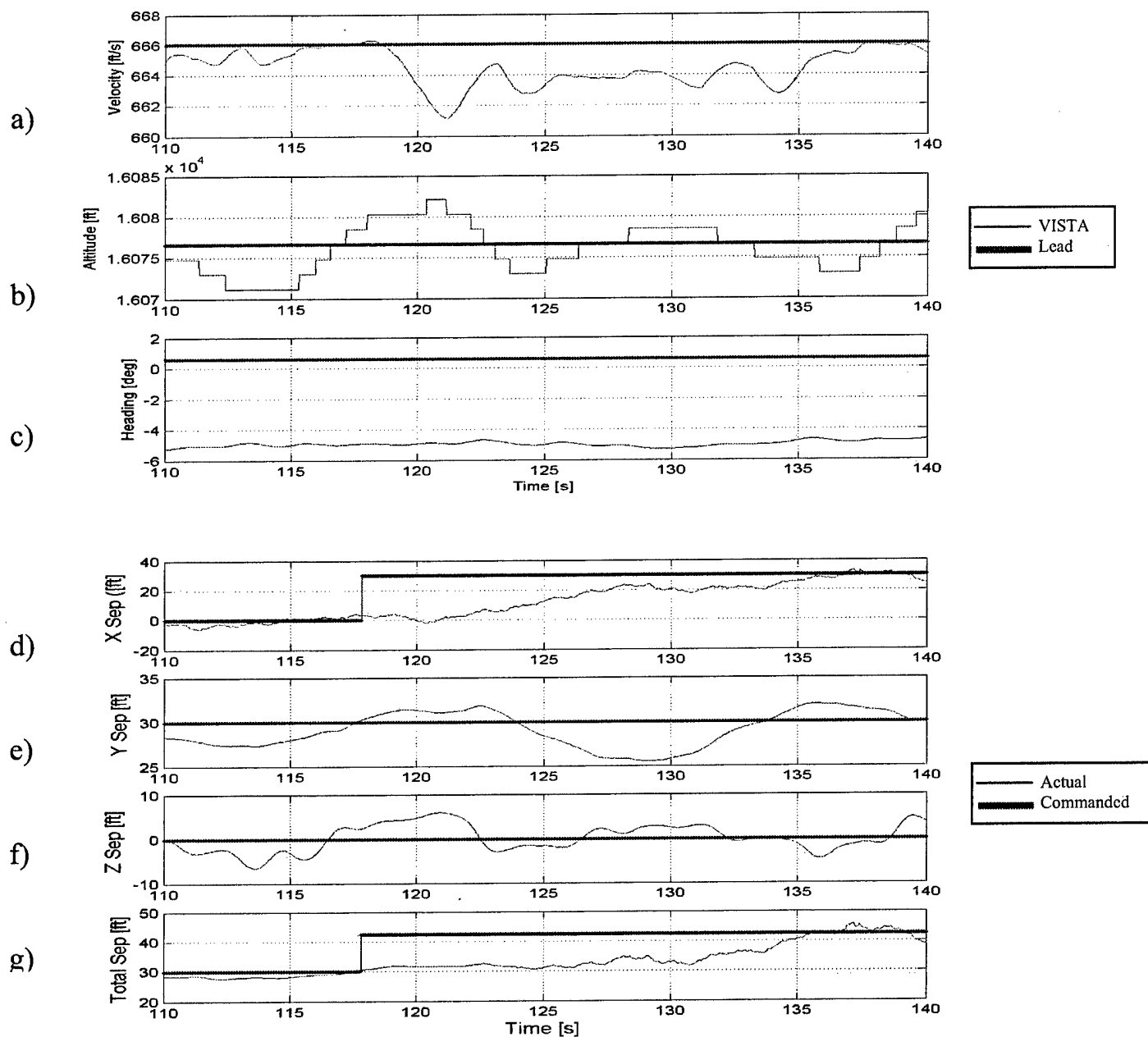
Figure 44 – Event 16A Run 2 (Sortie 3 Record 14)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	44.0	19.0	4.9	19.6
Time of maximum error (seconds)	13.2	1.0	2.8	1.0
Position Change	VISTA moves back 30 feet from (0 30 0) back to standard position (30 30 0)			

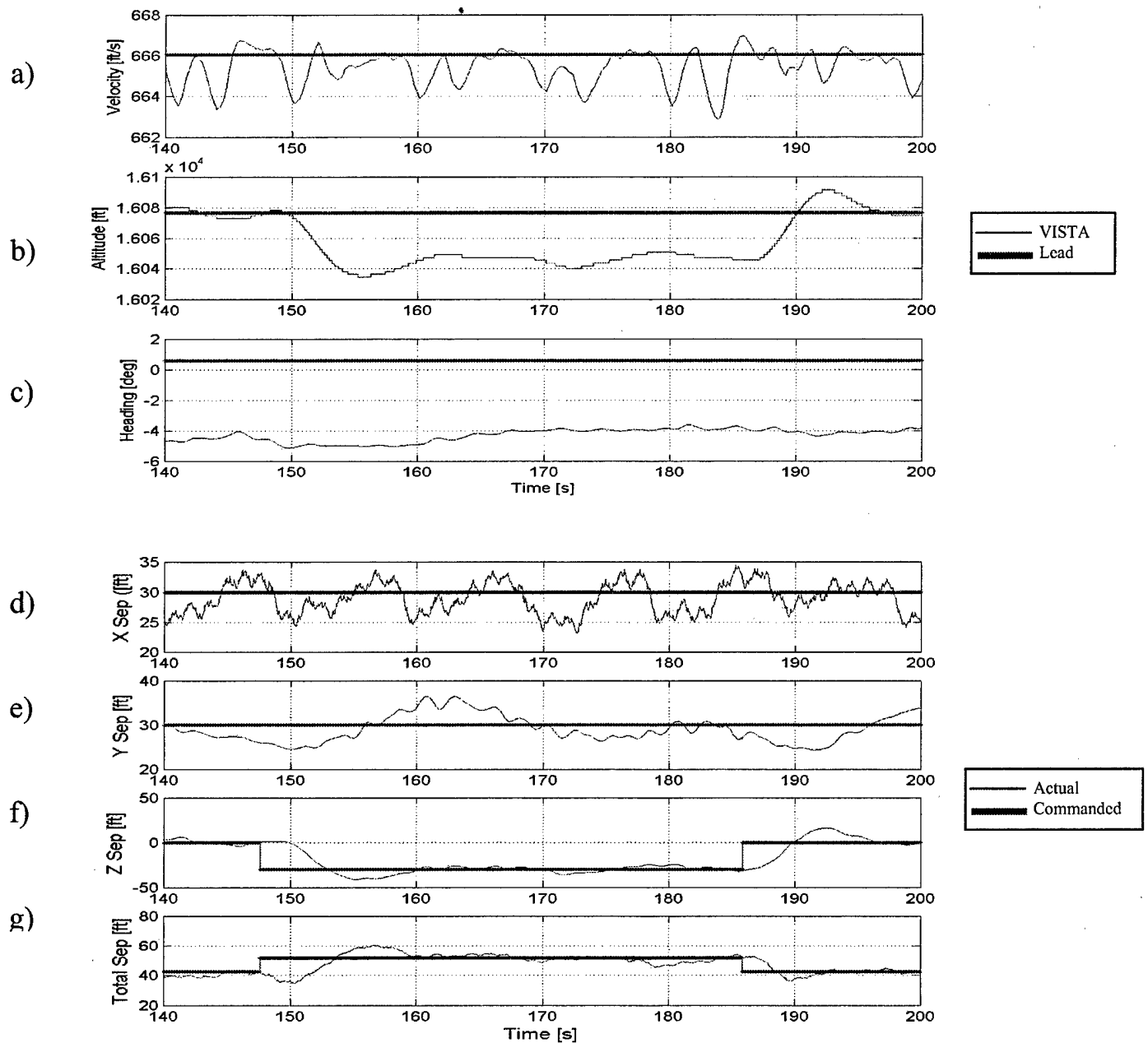
Figure 45 – Event 16B Run 1 (Sortie 1 Record 32)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		32.0	4.5	6.5	12.0
Time of maximum error (seconds)		120.4	128.9	113.6	137.2
Position Change	VISTA moves back 30 feet from (0 30 0) back to standard position (30 30 0)				

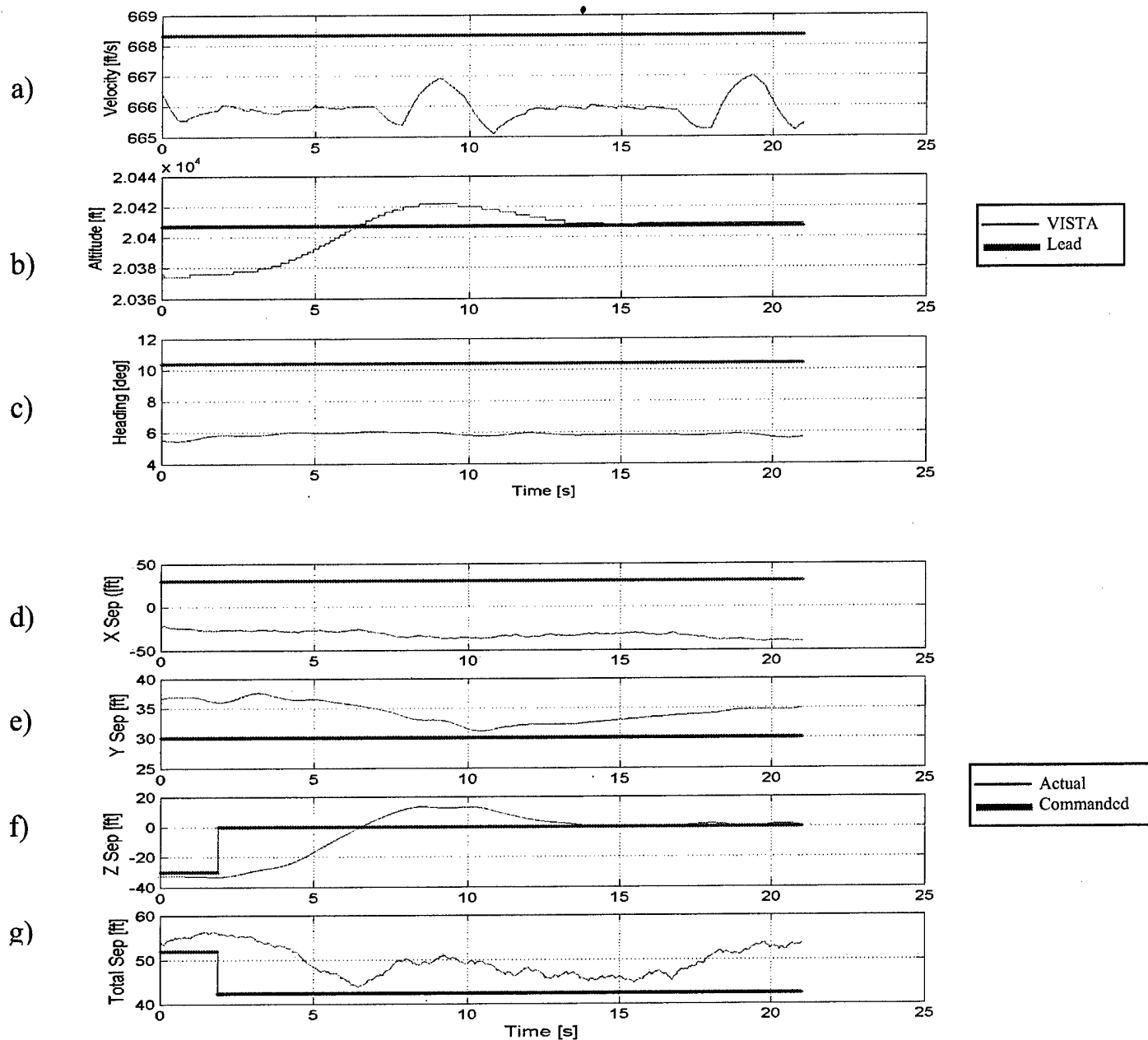
Figure 46 – Event 16B Run 2 (Sortie 3 Record 14)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

		X	Y	Z	Total Separation
Maximum Error (feet)		6.8	6.4	32.1	8.5
Time of maximum error (seconds)		172.7	160.8	185.8	156.7
Position Change	VISTA descends 30 feet to (30 30 -30) from standard position (30 30 0) and then climbs 30 feet back to standard position (30 30 0)				

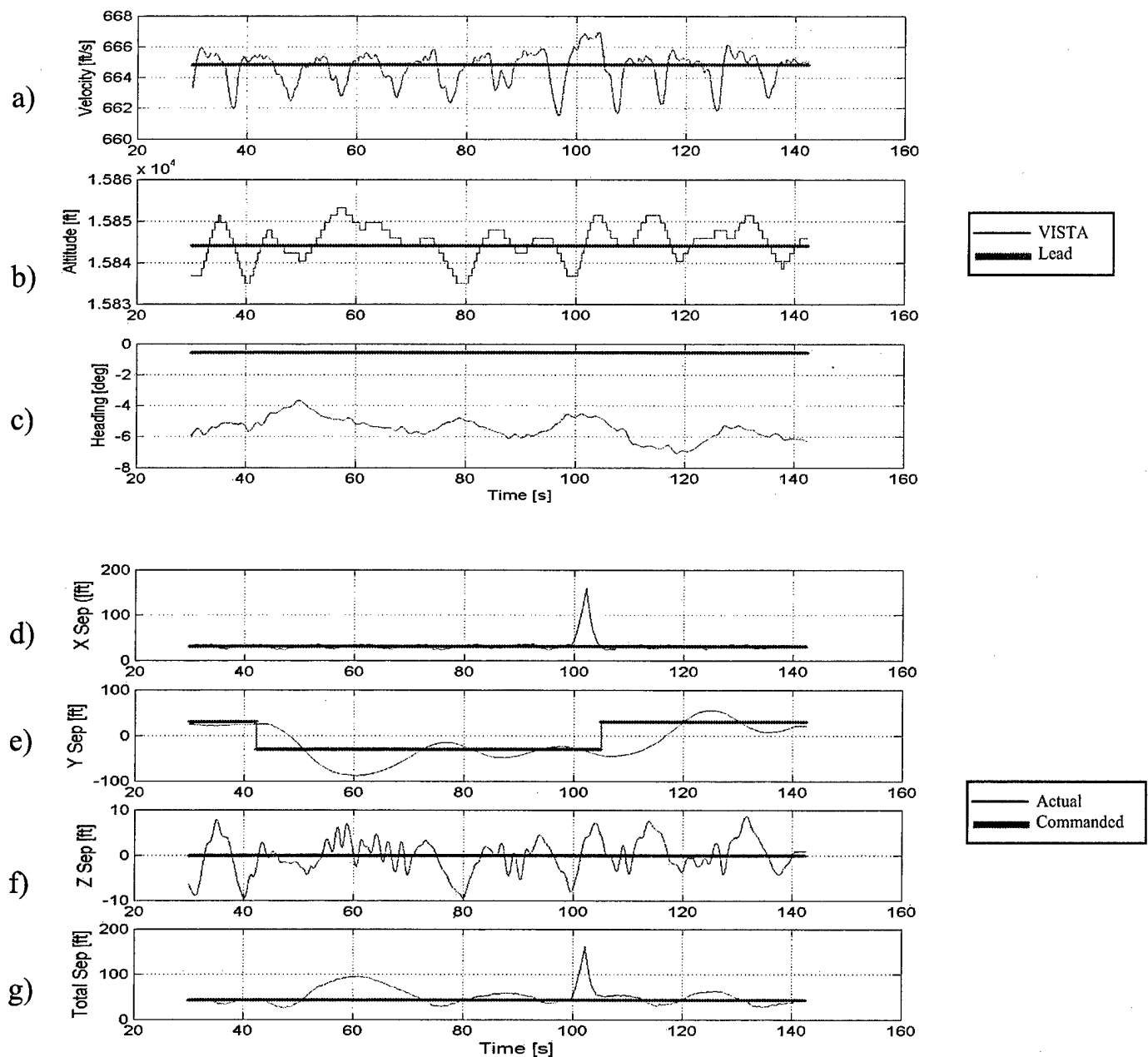
Figure 47 – Event 17A & B Run 1(A) 2(B) (Sortie 3 Record 14)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 25Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	71.0	7.6	33.3	4.4
Time of maximum error (seconds)	19.8	3.2	1.9	1.4
Position Change	VISTA climbs 30 feet from (30 30 -30) back to standard position (30 30 0)			

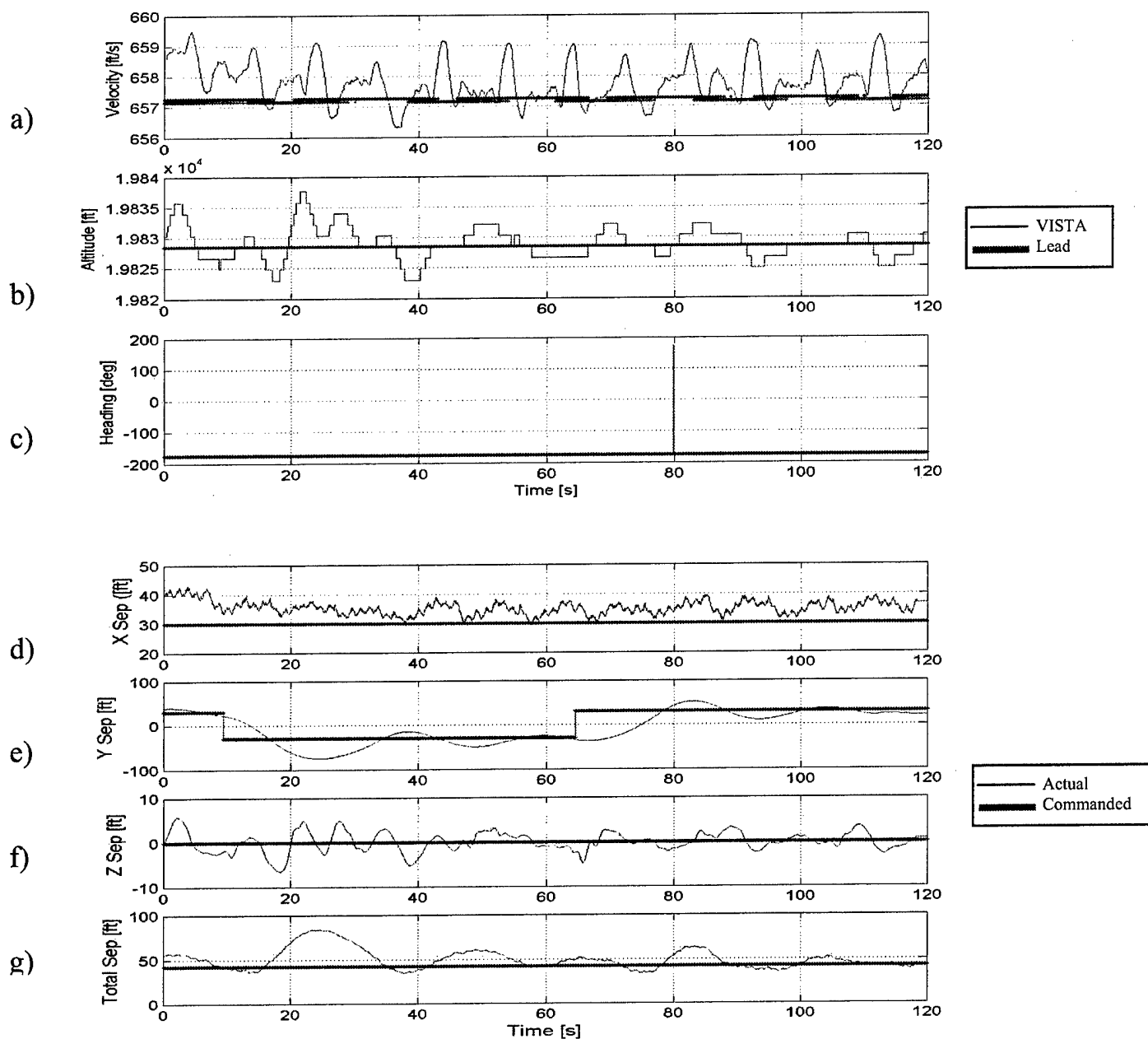
Figure 48 – Event 17B Run 1 (Sortie 1 Record 34)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 26Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	129.3	75.6	9.5	120.3
Time of maximum error (seconds)	102.2	107.0	79.9	102.2
Position Change	VISTA moves right 60 feet to (30 -30 0) from standard (30 30 0) position and then moves left 60 feet back to standard position (30 30 0)			

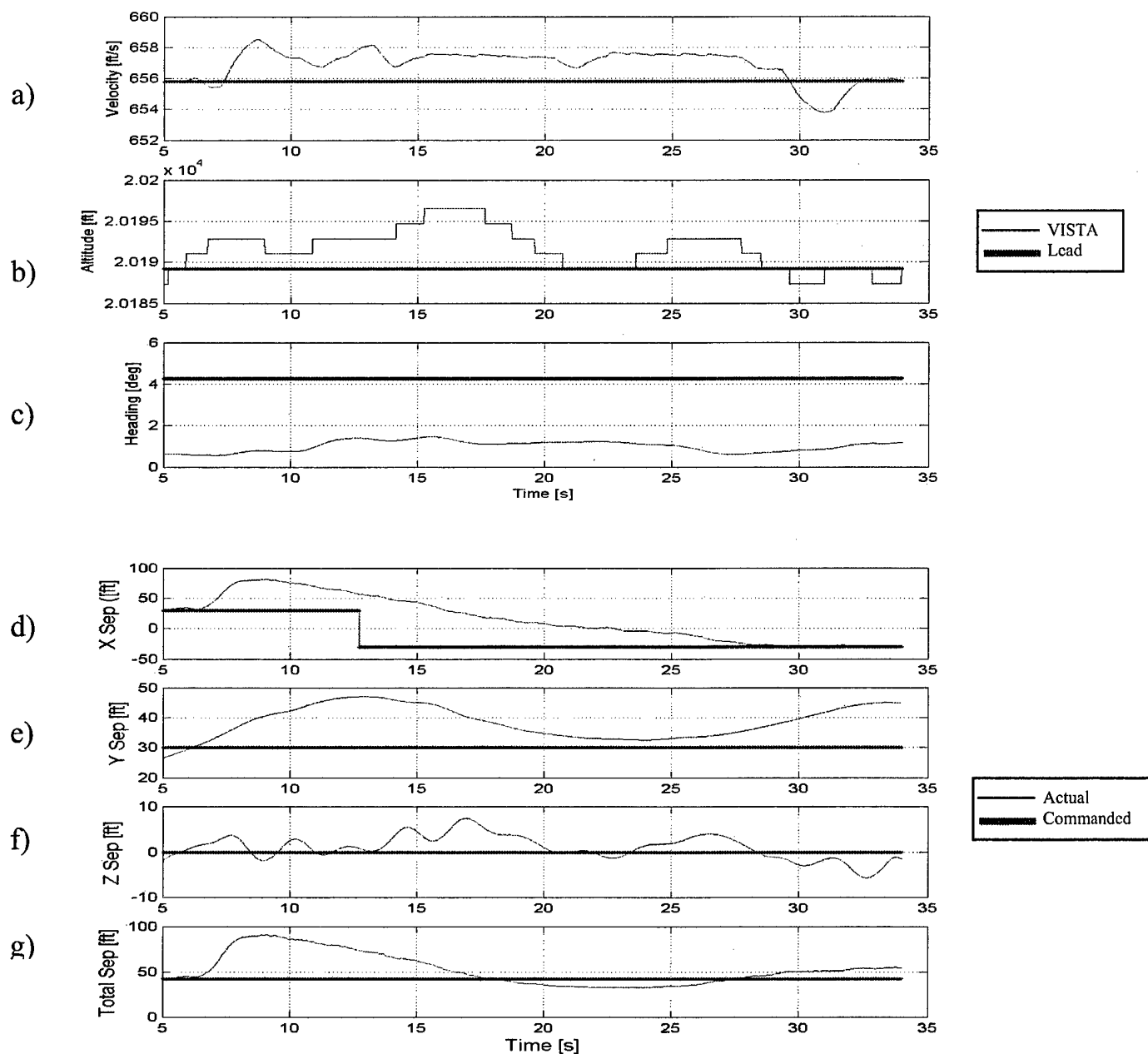
Figure 49 – Event 18A & B Run 1 (Sortie 3 Record 16)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	12.9	67.8	6.6	41.5
Time of maximum error (seconds)	3.8	66.5	18.4	24.8
Position Change	VISTA moves right 60 feet to (30 -30 0) from standard (30 30 0) position and then moves left 60 feet back to standard position (30 30 0)			

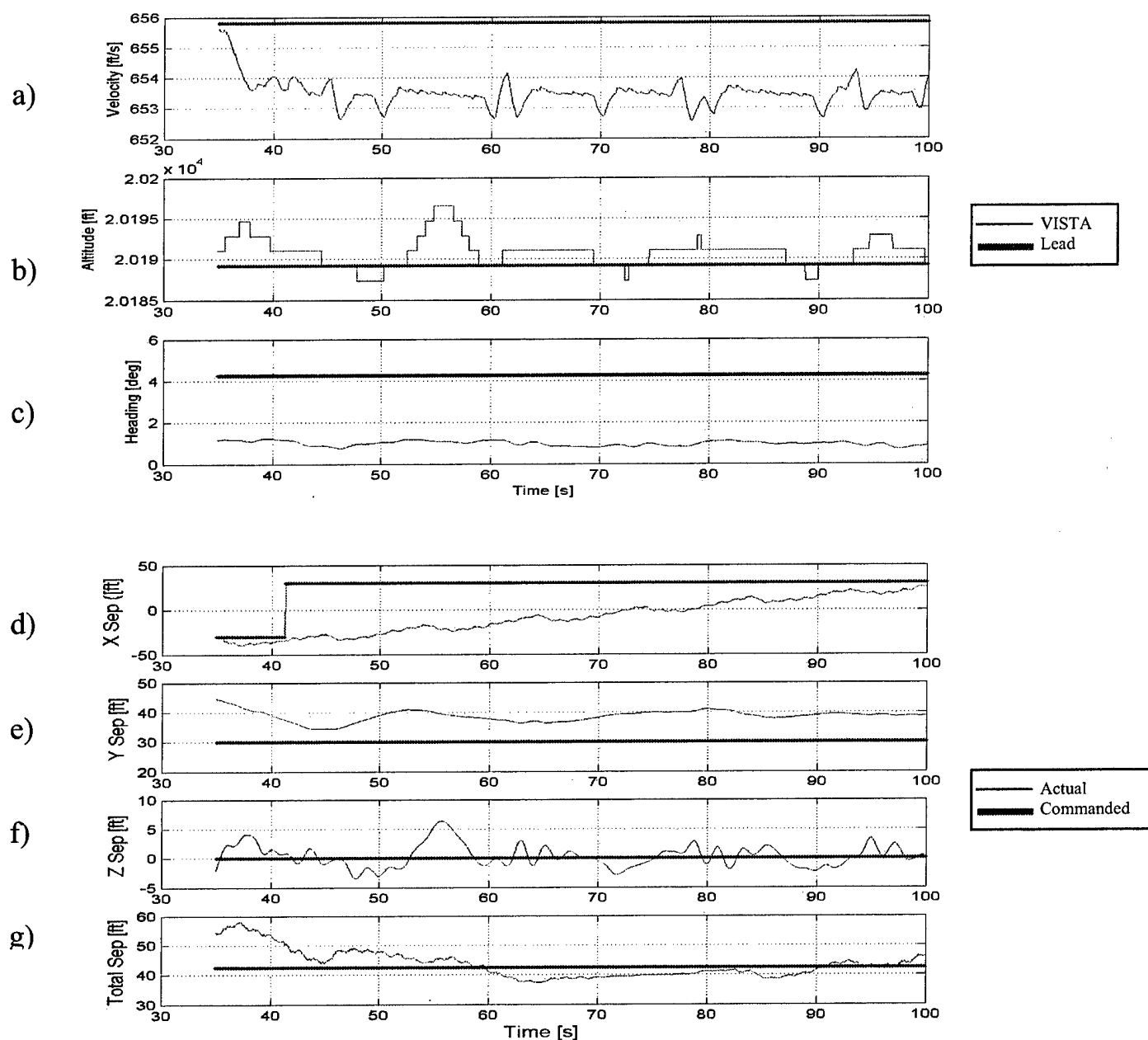
Figure 50 – Event 18A & B Run 2 (Sortie 4 Record 15)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	86.6	17.0	7.4	48.5
Time of maximum error (seconds)	12.8	12.7	16.9	9.1
Position Change	VISTA moves forward 60 feet to (-30 30 0) from standard position (30 30 0)			

Figure 51 – Event 19A Run 1 (Sortie 4 Record 6)



Data Basis: Flight Test; Test A/C: NF-16D #86-00048;  
 Engine: F110-GE-100; Configuration: Cruise, FCL; Test Date: 27Oct04

	X	Y	Z	Total Separation
Maximum Error (feet)	64.8	14.6	6.4	15.7
Time of maximum error (seconds)	41.3	35.0	55.7	37.3
Position Change	VISTA moves aft 60 feet from (-30 30 0) back to standard position (30 30 0)			

Figure 52 – Event 19B Run 1 (Sortie 4 Record 6)

## **Appendix F – Lessons Learned**

## Lessons Learned

During the calibration flights, the DSix-generated lead flew in a windless environment with inertial airspeed. The Variable Stability In-Flight Simulator Test Aircraft (VISTA), in contrast, flew in an actual air mass, and the VISTA's true airspeed was input to the Automatic Formation Flight Controller (AFFC). Thus the VISTA's airspeed and virtual lead's airspeed had a velocity mismatch equal to the winds aloft during the test point. This mismatch created a velocity error in the controller. Combined with the error-limiting feature of the control algorithm, the AFFC did not have enough control authority to keep the VISTA in position if the headwind or tailwind component of the winds aloft grew too large. An initial workaround was to fly on a heading that minimized the headwind or tailwind component of the winds aloft. However, considering air mass velocities of 60 knots or more at the test altitude, any deviation off of the desired heading would result in the VISTA running away from lead or falling behind.

Since expanding the error limits could have caused an instability, the velocity mismatch was instead corrected by inputting the VISTA inertial airspeeds from the Inertial Navigation Unit (INU) to the AFFC. Unfortunately, the test results demonstrated a persistent velocity error dependent on VISTA heading, though the error tended to be smaller in magnitude and opposite in sign to that in the calibration flights. The test team could not determine the source of the velocity error but suspected that true airspeed was somehow being input to the controller.

Future testing with a virtual lead aircraft generated by a ground station will undoubtedly need to tackle the velocity issue. Rather than inputting the VISTA's true airspeed to the controller, perhaps a better solution would be to implement an empirical wind model in the DSix to simulate the virtual lead flying in the same air mass as the VISTA. The inputs to the wind model could be generated real-time by the VISTA's INU. An added benefit is that this methodology would more closely simulate the actual environment in which a real two-ship formation would fly.

On one particular data flight, the VISTA's INU tumbled. The aircraft immediately entered a large-deflection aileron roll to approximately 135 degrees, as the INU was the AFFC's sole attitude reference. This incident could serve as a valuable lesson learned for future testing, especially if test points decrease in altitude, or if two actual aircraft are used for testing. Future testing should consider the amount of redundancy required in the flight computers and attitude reference to allow safe testing.

Finally, the Situation Awareness Data Link (SADL) was not particularly well suited for the transmission of continuous signals. Numerous data dropouts prevented successful AFFC engagements and corrupted error-keeping data. Additionally, the quality of the SADL data was very dependent on aircraft heading. The highest quality data were received on a north-westerly heading at least ten miles north of Edwards AFB. In our opinion, of all the challenges faced during testing, the data link had the greatest impact on data quantity and quality. As recommended in this report, future testing should consider using a more robust data link.

## **Appendix G – List of Abbreviations**

## List of Abbreviations

AFFC.....	Automatic Formation Flight Controller
AFFTC .....	Air Force Flight Test Center
AFIT.....	Air Force Institute of Technology
AFRL .....	Air Force Research Labs
DAS.....	Data Acquisition System
DFLCS .....	Digital Flight Control System
DO.....	Director of Operations
FCS .....	Flight Control System
FMO.....	Frequency Management Organization
FTE .....	Flight Test Engineer
GD-AIS .....	General Dynamics Advanced Information Systems
HITL .....	Hardware-in-the-Loop
HUD.....	Head-Up Display
ICE .....	Innovative Control Effector
INU .....	Inertial Navigation Unit
KCAS.....	Knots Calibrated Airspeed
KGS.....	Knots Groundspeed
KTAS .....	Knots True Airspeed
MFD.....	Multi-Function Display
MOP.....	Measure of Performance
NED .....	North-East-Down
NM.....	Nautical Mile
PAR.....	Program Assessment Review
PCMCIA .....	Personal Computer Memory Card International Association
PF .....	Pilot Flying
PNF .....	Pilot Not Flying
ROC .....	Rate of Climb
ROD .....	Rate of Descent
SADL .....	Situation Awareness Data-Link
TC .....	Test Conductor
TDY .....	Temporary Duty
TM.....	Telemetry
TMP .....	Test Management Project
TPS.....	Test Pilot School
UAV.....	Unmanned Aerial Vehicles
VIM.....	Vehicle Integrity Monitor
VISTA.....	Variable Stability In-Flight Simulator Test Aircraft
VMC .....	Visual Meteorological Conditions
VSS .....	VISTA Simulation System

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